US-Russian Joint Coordinating Committee on Radiation Effects Research
Project 1.1

DEVELOPMENT OF AN IMPROVED DOSE RECONSTRUCTION SYSTEM FOR THE GENERAL POPULATION AFFECTED BY THE OPERATION OF THE MAYAK PRODUCTION ASSOCIATION

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TABLE OF CONTENTS

1. INTRODUCTION

Russian and United States scientists have been involved in collaborative research programs under the sponsorship of the U.S.–Russian Joint Coordinating Committee on Radiation Effects Research (JCCRER) since 1995. JCCRER Project 1.1 is a comprehensive program to develop improvements in the dosimetry system for the population exposed as a result of the releases of the Mayak Production Association (MPA) by providing

- More in-depth analysis of existing data,
- Further search of existing records for useful data,
- Model development and testing,
- Evaluation of uncertainties,
- Verification of procedures, and
- Validation studies of existing and planned results.

The planned details of the project were specified in the proposal document (Degteva et al. 1996a).

The specific aim of this project is to enhance reconstruction of external and internal radiation doses for 30,000 individuals who resided in the valley of the Techa River, which was contaminated in 1949–1956 by the discharges of liquid radioactive wastes from the MPA. The purpose of the enhanced dose reconstruction is to support companion epidemiologic studies of radiogenic leukemia and solid cancers (NCI-RERF-URCRM Project and JCCRER Project 1.2).

The results of the current study have been presented in progress reports, milestone reports, and papers published in peer-reviewed journals (the list of all publications is given in Appendix 1). This is a final report integrating (not repeating) the achievements obtained for the three-year period of joint activity in the framework of JCCRER Project 1.1.

The purposes of this document are the following:

1. To provide a description of an improved dosimetry system referred to as the Techa River Dosimetry System-2000 (TRDS-2000);
2. To summarize updated assessments of external and internal doses calculated for members of the Techa River Cohort using the TRDS-2000;
3. To describe quality assurance work accomplished for the main databases; and to describe work on the verification and validation of the models used in the TRDS-2000;
4. To describe the approaches to TRDS-2000 uncertainty assessments for external and internal doses; and
5. To outline proposed future directions that can be undertaken to provide additional improvements in the dosimetry system.

2. BACKGROUND

Population exposure in the Urals region occurred as a result of failures in the technological processes in the Mayak plutonium facility in the late 1940's and early 1950's. A major source of environmental contamination was the discharge of about 10^{17} Bq of liquid wastes into the Techa River in 1949–1956. Residents of many villages downstream from the site of release (Fig. 1 and Table 1) were exposed via a variety of pathways; the more significant included drinking of water from the river and external gamma exposure due to proximity to bottom sediments and the shoreline. There are known to be additional sources of exposure for the Urals population. The most important was an explosion in the radioactive waste-storage facility in 1957 (the so-called Kyshtym accident) that formed the East Urals Radioactive Trace (EURT) due to dispersion of 7.4×10^{16} Bq into the atmosphere. Some of this material contaminated villages to which persons exposed on the Techa River had been relocated. Other possible sources of confounding exposure include the gaseous aerosol releases from the Mayak facility in 1949–1957 and the windblown contamination from Lake Karachay when it dried out in 1967.

The series of radioactive releases that occurred in the same region in different years and the intensive migration of the population within the contaminated area are specific features of the Urals situation. This determined the approach to follow-up: selecting a fixed cohort and tracing all places of residence for each subject in the cohort since the beginning of radioactive contamination.

2.1. THE COHORTS OF INTEREST

In 1968 the Techa River Registry was created at the Urals Research Center for Radiation Medicine (URCRM) with the goal of including residents of villages along the Techa River who lived there during the period of high exposure from 1949 through 1952. The registry includes data on 26,500 such persons, and these persons have been identified as the "Techa River Cohort" (TRC). The TRC has been studied for several decades by scientists from the URCRM, and an increase in both leukemia and solid cancers with radiation dose has been noted (Kossenko et al. 1997). This finding suggests that, with continuing improvements in the quality of the follow-up and dosimetry, study of the TRC has the potential to provide quantitative estimates of the risks of stochastic health effects produced by chronic low-dose-rate radiation exposure in the general population.

In more recent times the "Extended Techa River Cohort" (ETRC) has been created; the ETRC includes the original TRC and about 5,000 persons who migrated to the villages after the period of high exposure but before 1960; the late entrants in the ETRC have been restricted to those born before 1949 as for the original TRC. This ETRC is the master cohort from which subcohorts can and are being drawn for analysis and for whom it is desirable and possible to calculate individualized internal and external doses.

The ETRC has many desirable features in terms of its continuing epidemiologic study:

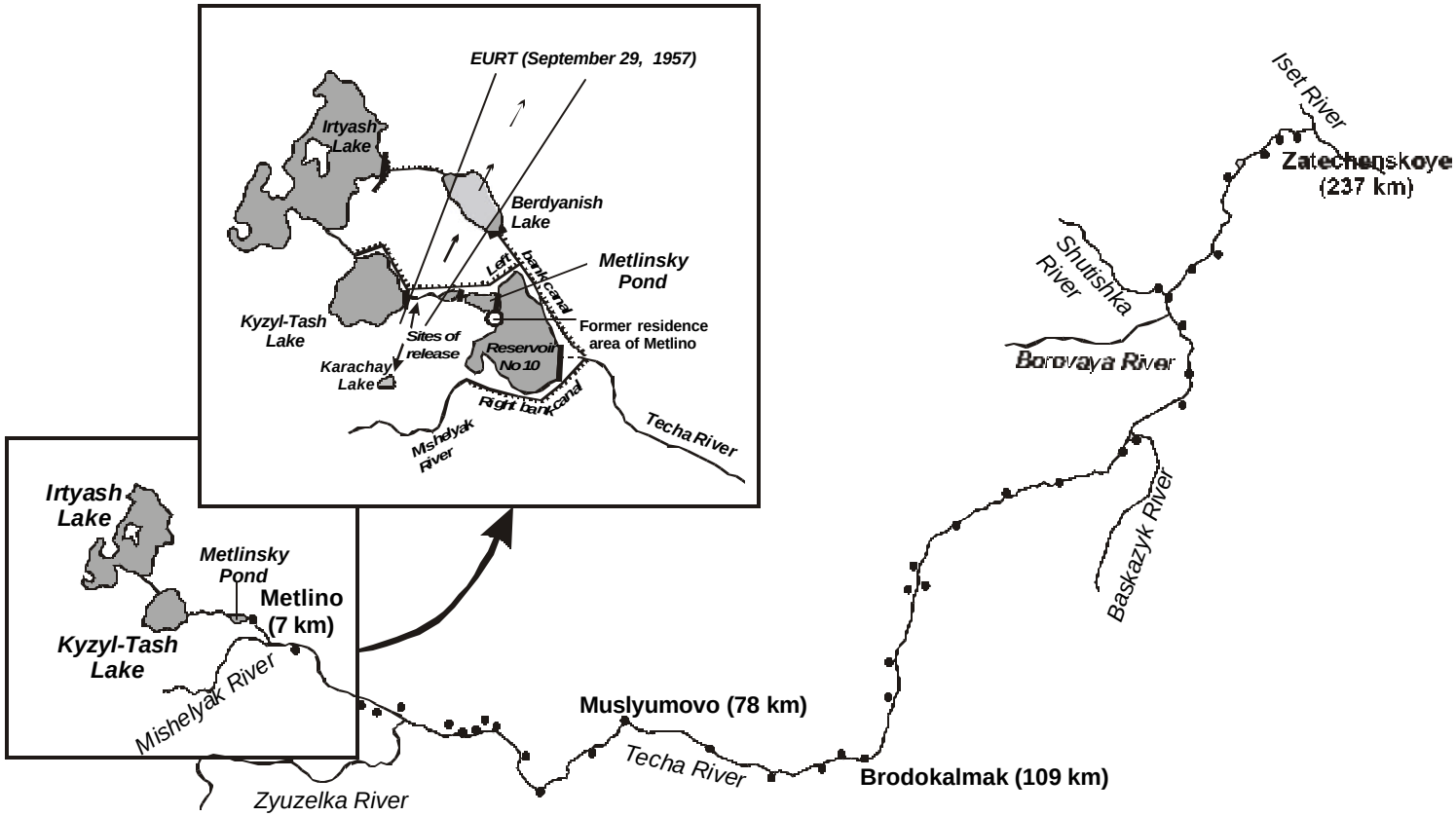


Fig. 1. Schematic map of the Techa River (approximate scale) and the villages located on its banks before contamination occurred (1949). The names of the major settlements and the distances from release site are also indicated. Schematic diagrams of the upper reaches of the Techa River and the East Urals Radioactive Trace (EURT) formed in 1957 are shown in the upper panel; the shaded area indicates the region of ^{90}Sr-deposition density greater than 740 MBq m^{-2} (20 Ci km^{-2}).

Table 1. The settlements along the Techa River involved in this study.

Settlement	Distance from site of release, km	Evacuation status
Metlino	7	Evacuated
Techa Brod	18	Evacuated
Asanovo and Nazarovo	33	Evacuated
M. Taskino	41	Evacuated
Gerasimovka	43	Evacuated
GRP	45	Evacuated
Nadyrov Most	48	Evacuated
Nadyrovo	50	Evacuated
Ibragimovo	54	Evacuated
Isaevo	60	Evacuated
Podssobnoe hoz.	65	Evacuated
Muslyumovo	78	Exists
Kurmanovo	88	Evacuated
Karpino	96	Evacuated
Zamanikha	100	Evacuated
Vetrodujka	105	Evacuated
Brodokalmak	109	Exists
Osolodka	125	Evacuated
Panovo	128	Evacuated
Cherepanovo	137	Evacuated
Russkaya Techa	138	Exists
Baklanovo	141	Evacuated
Nizhnepetropavlovskoye	148	Exists
Beloyarka-2	155	Evacuated
Lobanovo	163	Exists
Anchugovo	170	Exists
Verkhnyaya Techa	176	Exists
Skilyagino	180	Exists
Bugaevo	186	Exists
Dubasovo	200	Exists
Bisserovo	202	Exists
Shutikhinskoye	203	Exists
Progress	207	Evacuated
Pershinskoye	212	Exists
Klyuchevskoye	223	Exists
Ganino and Markovo	230	Evacuated
Zatechenskoye	237	Exists

- The cohort consists of members of the general population;
- Members of the cohort are relatively old at this time, the youngest member is 50 years old;
- The years at risk are relatively large, about 50 years; and
- The doses received by this population are relatively large; 5% of the members have red bone-marrow doses due to ^{90}Sr of >1 Gy; in addition some members of the cohort have external doses of up to 0.4 Gy.

Further, the URCRM Registry includes data on 29,700 persons exposed in utero and/or the progeny of exposed parents. Twelve thousand such persons who are the children of TRC members have been identified as the "Techa River Offspring Cohort" (TROC). The TROC has the potential to provide direct data on radiogenic health effects in progeny that resulted from exposure of a general population to chronic low-dose-rate radiation.

2.2. THE URCRM DATABASES

There are several databases located at the URCRM that are used jointly by dosimetrists and epidemiologists working together on population risk-assessment projects. All databases are located on a central server, which is managed by a System Administrator. The administrator controls access to the system through a double layered system. Only specified work stations can access the system and only certain work stations are allowed to alter specific parts of the database. For example, only a work station within the Registry Department would be allowed to alter data concerning vital status determination. In addition, an individual may only access the system according to a password. The System Administrator also makes a backup on streaming tape of the URCRM databases and working files on a daily basis. Additional backups on weekly, monthly, and yearly bases are also made; these tapes are stored in a safe at the URCRM.

Database MAN. One of the more important URCRM databases is database MAN (Degteva et al. 1996c); the details of database MAN are indicated in Fig. 2. The purpose of database MAN is to be the central repository of all "input" data pertaining to a member of the Techa River Cohort. This information includes all identification data; pedigree or family information; data on migration from location to location; the last known address; information on the deceased at time of death, etc.; the cause(s) of death; the diagnoses in addition to and including the cause(s) of death; and available information on measurements of body burdens of radionuclides and beta counts of teeth and forehead bone. All information pertaining to a particular member of the registry is accessed via a "system number," designated as "SN." In more recent times this system number has also been referred to as an "Identification Code" or

This comprehensive database is maintained as a joint effort at the URCRM by members of the Epidemiologic Laboratory concerning International Disease Classification-9 codes; members of the Registry Department concerning vital status, migration, last address, etc.; and members of the Biophysics Laboratory concerning measurements of body content, etc. Members of all three groups have free access to these data, but only the responsible group has the authority and ability to change the data for which it is responsible.

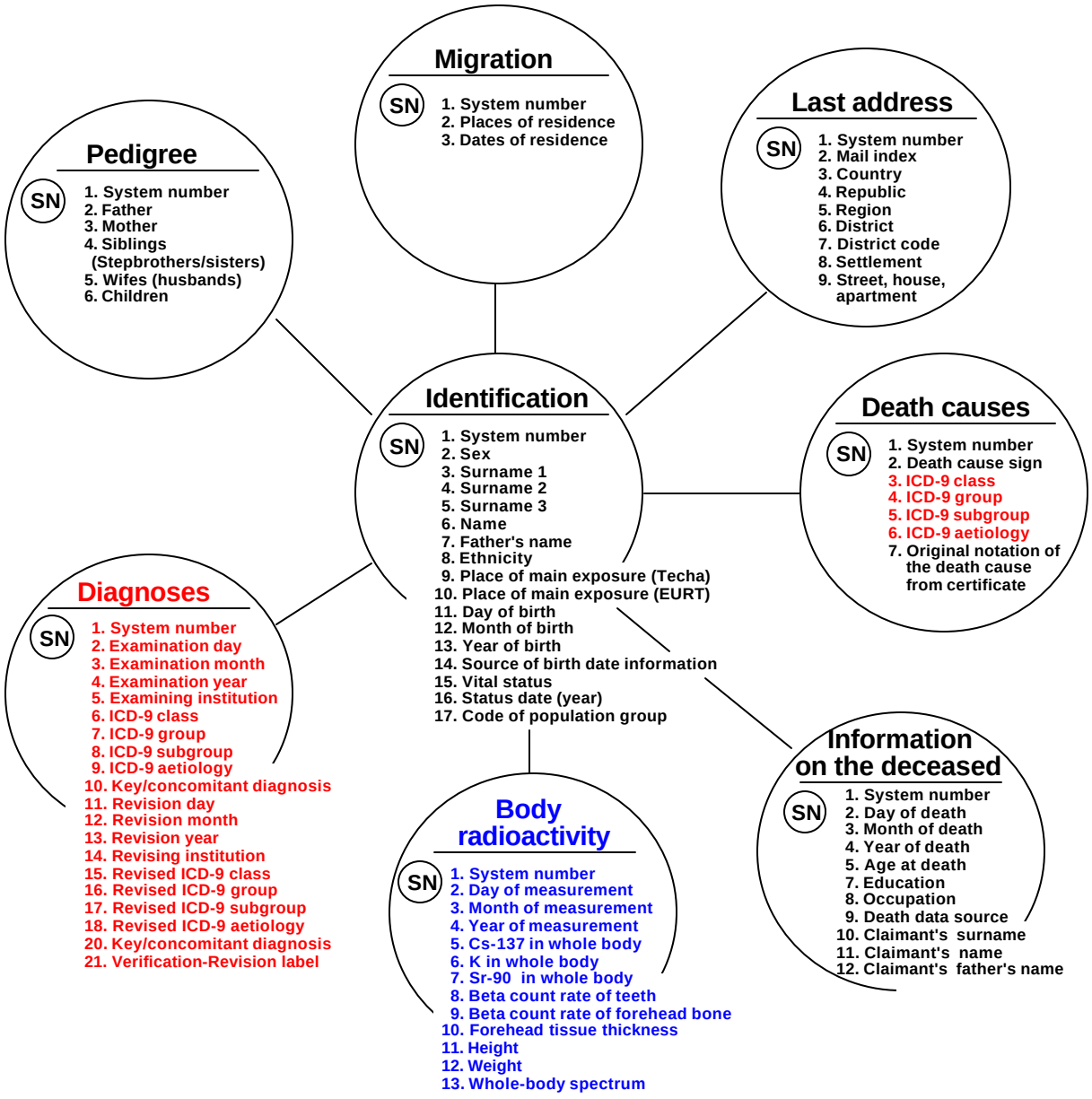


Fig. 2. Information contained in database MAN. Information shown above in red is the responsibility of the Epidemiology Laboratory; information shown in blue is the responsibility of the Biophysics Laboratory; other information is the responsibility of the Registry Department.

Database ENVIRONMENT. This database contains available data on source terms, measurements of radionuclides in river water and sediment, and external gamma-exposure rates in the environment. In addition, hydrological data pertaining to the Techa River are included. The contents of database ENVIRONMENT were summarized and described in detail in a

previous publication (Degteva et al. 1996c). This database is the responsibility of the URCRM Environmental Department and the Biophysics Laboratory and is available to the other groups. The link between databases MAN and ENVIRONMENT is accessed via a "settlement code," which is the same identifier both for the residence place of exposed persons and for all environmental measurements in this site.

Other databases. There are several other databases that contain primary data and which could be used for risk analysis. The more important are the Tumor and Autopsy Registries. The Tumor Registry contains 25,500 copies of Regional Cancer Dispensary notifications for the residents of the catchment area, and the Autopsy Registry contains post-mortem diagnoses and ^{90}Sr measurements in bone samples for 5,400 subjects who lived in the Urals. Both registries have been matched to the Techa River Registry. These two registries were found to include data for members of the ETRC concerning about 4,000 tumors and 800 measured samples of bones.

2.3. FREEZING OF THE COHORTS AND DATABASES FOR ANALYSIS

Personal data and residence-history data for subjects under observation are occasionally updated and corrected in accordance with newly received archival documents, interviews and other data. On the basis of such new information, subjects are sometimes moved from one cohort to another within database MAN. Also, status changes through a variety of processes such as death, marriage, or migration; newly born persons are added to the Offspring Cohort. Also, the dosimetric measurements are continuing. Updated information of these and other types are occasionally entered into the appropriate databases.

At various times in the past the TRC and its associated databases have been "frozen" for analysis. This practice is very similar to that used by the Radiation Effects Research Foundation (RERF) in their studies of the Life Span Study (LSS) cohort. Thus, while work continues on following up members of the cohort and in improving the dosimetry, these changes are not implemented on a piecemeal approach. Rather, at selected dates of "freezing" the cohort and its databases for analysis, the changes that have progressed incrementally over several years are implemented at once for future analysis. The dates of the "freezings" are mutually agreed upon by the epidemiologists and dosimetrists involved in joint study on radiation-risk analysis. In recent years such freezings have occurred for 1989 and 1996. Future plans include freezes for 2000 and perhaps 2005. A brief description of each of these events follows.

1989 freeze of the cohort. The most recent analysis of the radiogenic effects observed in the TRC was provided in Kossenko et al. (1997). This analysis was performed in 1993–1994, but there had been no active ascertainment of vital status for cohort members since the early 1980s. However, copies of death certificates through the end of 1989 had been obtained for those areas of the epidemiologic catchment area located in Chelyabinsk Oblast. Thus, the analysis was fixed on the date of 1989, although vital status was unknown for a significant fraction of the cohort. In spite of these limitations, an increase in both leukemia and other cancers associated with increasing dose was noted.

The method of dose reconstruction used for the 1989 freeze of the cohort is also provided in (Kossenko et al. 1997). This method was essentially that described by Degteva et al. (1994)

with some improvements. Significant features of the dosimetry for 1989 freeze were the following:

- Internal doses from ^{90}Sr were calculated for an individual on the basis of group doses for the village where a person received his major exposure;
- Internal doses from ^{89}Sr and ^{137}Cs were derived from ^{90}Sr dose according to the relative concentration in river water for the reference site; and
- External doses were based upon measured exposure rates along the river bank and estimated age-specific life styles (concerning time spent on the river bank, etc.).

1996 freeze of the cohort. The extended cohort (ETRC) was created for this fixing of the cohort and its databases by the addition of about 5,000 persons who were late entrants to the villages and who received smaller exposures. The 1996 freeze represents the current state of the URCRM databases, which are currently undergoing statistical analysis; no derivations of risk factors from the 1996 version of the database have been published.

Several significant improvements were made in the dosimetry for the 1996 freeze. These included the first implementation of the Techa River Dosimetry System (TRDS-96), which has been described by Degteva et al. (1996e). A major improvement included use of individual-residence histories, so that adequate attention could be given to the exposure received in each location where an individual lived. TRDS-96 was successfully operated at the URCRM and provided an initial look at dose distributions among ETRC members. TRDS-96 treated all ETRC members using a single dose-assessment protocol based on individual-residence histories available for all cohort members. The experience gained by the use of TRDS-96 paved the way for an improved system, which incorporated further developments in dosimetry using TRDS-96 as a prototype-dosimetry system.

3. TRDS-2000 DESCRIPTION

The improved dosimetry system is referred to as TRDS-2000. Agreement has been reached that the next freeze of the cohort and its databases will occur in the year 2000. This will be the first time that advantage can be taken of the major improvements in epidemiologic follow-up and in dose reconstruction.

Major activities leading to improvements in the TRDS-2000 include

- A comprehensive, analytical review (Vorobiova et al. 1997; 1999b) of historical data on radionuclide releases to the Techa River, measured concentrations of radionuclides in water and in sediments of the Techa River, hydrological data, and measured external gamma-exposure rates at and nearby the river;
- The development (Vorobiova and Degteva 1999) of a river model to describe the time- and distance-dependent radionuclide concentrations and exposure rates along the Techa River;

- Use of the model and other data to compute individual-body-burden histories and resulting internal doses (Tolstykh et al. 1998) from all radionuclides, including short-lived radionuclides that had not been included in TRDS-96;
- A major revision (Vorobiova et al. 1999a) in the computation of external dose based upon the upgraded TRDS approach, the river model, a re-evaluation of all measurements of external gamma-exposure rates near the shoreline and in the living areas, and a re-examination of data pertaining to the amounts of time spent near the river and in other locations; and
- Evaluation for the first time of the uncertainty in the calculated doses for members of the ETRC.

A preliminary description of the general approaches and initial data sets used for the creation of the TRDS was provided by Degteva et al. (1996b). The TRDS is designed as a modular database processor. That is, depending on the input data for an individual, various elements of several TRDS databases are combined to provide the dosimetric variables requested by the user. The input data include the following information for each member of the ETRC: identification code, year of birth, year of entry to the catchment area, year of migration from the catchment area, year of vital status determination, and residence history within the contaminated areas. These data are prepared and updated by members of the Registry Department who are working on companion epidemiologic studies.

3.1. BASIC EQUATIONS FOR DOSE CALCULATIONS

The method being used for the TRDS-2000 basic dose calculations is relatively simple and can be written as a single equation:

$$D_{o,Y} = \sum_{y=1}^{P} \sum_{L} M_{y,L} \left[\left(\sum_{r} I_{y,r,L} \cdot DF_{r,o,Y-y} \right) + A_o \left(D_{Riv,L,y} \cdot T_1 + D_{Out,L,y} \cdot T_2 + D_{In,L,y} \cdot T_3 \right) \right],$$

where

$D_{o,Y}$ = Absorbed dose (Gy) in organ o accumulated to calendar year Y;
Y = The calculational endpoint for a particular individual (can vary within the range 1950–2005);
y = Year of environmental exposure (external irradiation and intake of radionuclides);
P = The endpoint of external exposure and intake of radionuclides for a particular individual (can vary within the range 1950–1959);
L = River-location (village) identifier;
$M_{y,L}$ = Fraction of year y spent in location L;
r = Identifier of ingested radionuclide (^{89}Sr, ^{90}Sr, ^{95}Zr, ^{95}Nb, ^{103}Ru, ^{106}Ru, ^{137}Cs, ^{141}Ce, or ^{144}Ce);
$I_{y,r,L}$ = Intake function (Bq year^{-1}) for year y, radionuclide r, and location L (function of age, related to y), further described below;

$DF_{r,o,Y\text{-}y}$ = Conversion factor (Gy Bq^{-1}) for dose accumulated in organ o in year Y-y from intake of radionuclide r in year y (function of age, related to y);
Y-y = Time since intake, years;
A_o = Conversion factor from absorbed dose in air to absorbed dose in organ o (function of age, related to y);
$D_{Riv,L,y}$ = Dose rate in air near river shoreline at location L in year y (Gy $year^{-1}$);
$D_{Out,L,y}$ = Dose rate in air outdoors within residence area at location L in year y (Gy $year^{-1}$);
$D_{In,L,y}$ = Dose rate in air indoors at location L in year y (Gy $year^{-1}$);
T_1 = Time spent on river bank (relative to whole year) (function of age, related to y);
T_2 = Time spent outdoors (relative to whole year) (function of age, related to y); and
T_3 = Time spent indoors (relative to whole year) (function of age, related to y).

The intake function $I_{y,r,L}$ for each year y is calculated as:

$$I_{r,L} = I_R^{Sr90} \times \alpha_{Age,R}^{Sr90} \times f_L^{Sr90} \times f_L^r \ ,$$

where

I_R^{Sr90} = Annual ^{90}Sr intake for adult residents of the reference settlement (Muslyumovo);
$\alpha_{Age,R}^{Sr90}$ = Annual ^{90}Sr intake for other age groups relative to that for adults living in the reference settlement;
f_L^{Sr90} = Annual ratio of ^{90}Sr intake for location L to ^{90}Sr intake for residents of the reference settlement; and
f_L^r = Annual ratio of nuclide-to-^{90}Sr in the intake for location L.

3.2. TRDS DATABASES

The TRDS relies on extensive databases to compute the doses for each cohort member. A summary of the system databases is presented in Table 2. These databases were calculated and modeled during the course of research performed in the frameworks of the current project. A full description of the models and data sets used for the production of the TRDS databases is provided in Degteva et al. (2000a,b,c).

To reconstruct annual dose rates near the river and within residence areas [$D_{Riv,L,y}$, $D_{Out,L,y}$, $D_{In,L,y}$ (database TECH_EXT)] all available results of exposure-rate measurements near the Techa River were retrieved from the URCRM archives and databases (Vorobiova et al. 1999a). To fill the gaps in measured data the Techa River model describing radionuclide transport from the site of release along the river and accumulation of radionuclides by bottom sediments (Vorobiova and Degteva 1999) was used. Dose rates in air on the river banks were calculated on the basis of modeled radionuclide concentrations in bottom sediments; for this purpose coefficients (Eckerman and Ryman 1993) obtained by Monte Carlo simulations of air kerma were used. The data in Table 3 are examples of data on dose rates near the river (Vorobiova et al. 1999a) for two selected settlements.

Table 2. TRDS system databases.

System DB	Form	Content	Model used	Source of data
TECH_LIST	File	List of Techa settlements and codes (L)	-	URCRM archives
TECH_EXT	Library of 39 files	For each of 39 settlements annual dose rates near the river and within residence areas ($D_{Riv,L,y}$, $D_{Out,L,y}$, $D_{In,L,y}$)	Techa River model	Database ENVIRON-MENT
REGIME	File	T_1, T_2, T_3 for age groups	Behavioral model	URCRM Reports
DOS_F	Library of nine files	For each of 9 organs, age-dependent dose-conversion factors (A_o)	Monte Carlo calculations	Literature
REPER	File	Annual ^{90}Sr intakes for adult residents of the reference settlement	Strontium-90 intake model	Database MAN
CHILD	File	Annual relative ^{90}Sr intakes for children who lived in the reference settlement	Strontium-90 intake model	Database MAN
NUCL_STC	Library of 39 files	Annual ratios of intake of ^{90}Sr for each of 38 settlements to that for reference settlement; and intake of nuclide-to-^{90}Sr for each of 39 settlements	Techa River model	Database MAN
^{90}Sr, ^{89}Sr	Two libraries, each of 31 files	Age- and time-dependent dose-conversion factors for different organs ($DF_{r,o,Y\text{-}y}$)	URCRM model for Sr metabolism	Database MAN
^{137}Cs, ^{103}Ru, ^{106}Ru, ^{95}Zr, ^{95}Nb, ^{144}Ce, ^{141}Ce	7 libraries, each of 9 files	Age- and time-dependent dose conversion factors for different organs ($DF_{r,o,Y\text{-}y}$)	ICRP-67 models	Literature

Table 3. Dose rate in air near the Techa River shoreline for sites in the upper and middle reaches of the river.

Calendar year	Dose rate in air, μGy h^{-1}	
	Metlino site (7 km from the site of release)	Muslyumovo site (78 km from the site of release)
1950	310	3.4
1951	1380	17.5
1952	470	5.5
1953	465	11
1954	250	9.9
1955	80	4.2
1956	80	4.2
Background	0.09–0.14	

Model behavior factors T_1, T_2, T_3 (database REGIME) were derived from observational data (Vorobiova et al. 1999a) from the 1950s of typical life-style patterns for different age groups of Techa Riverside residents. Table 4 exemplifies the data on behavior factors for different age groups.

Age-dependent conversion factors from absorbed dose in air to absorbed dose in organs, A_o (database DOS_F), were taken from the literature (Eckerman and Ryman 1993; Petoussi et al. 1991). Table 5 exemplifies the data on conversion factors for different age groups.

As indicated in the basic dose equation, a key parameter in determining internal dose is the annual average-intake function, $I_{y,r,L}$, of radionuclide r in year y at location L. This function is estimated from measurements of radionuclides in residents of Techa River villages. The function has four factors: intakes of ^{90}Sr as a function of calendar year in adult residents of the village of Muslyumovo (database REPER); the ratio of ^{90}Sr intakes as a function of age and calendar year for children to that for adults in Muslyumovo (database CHILD); the ratio of ^{90}Sr

Table 4. Typical life patterns for different age groups of the Techa Riverside residents.

Age group, years	Period of time spent at specified site, hours per year			
	Shoreline (summer time)	Residence area (outdoors)	Residence area (indoors)	Far from the river (uncontaminated territory)
<7	45	2235	6480	0
7–15	150	2130	5760	720
16–59	150	1410	3960	3240
≥60	150	2490	6120	0

Table 5. Conversion-factor ratios: Absorbed dose in organ-to-absorbed dose in air.

Organ	Age-dependent dose-conversion factors, Gy Gy^{-1}		
	<7 y	7–17 y	≥17 y
Red bone marrow	0.85	0.76	0.73
Bone surface	1.37	1.22	1.18
Large Intestinal wall	0.75	0.67	0.64
Small Intestinal wall	0.73	0.65	0.62
Stomach wall	0.78	0.69	0.66
Testes	0.94	0.83	0.80
Ovaries	0.71	0.63	0.61
Uterus	0.72	0.64	0.62

intakes in other villages to that in Muslyumovo (database NUCL_STC); and the annual ratios of the intakes of other radionuclides to the intake of ^{90}Sr (database NUCL_STC).

The most important radionuclide from a dosimetric standpoint for the affected population is ^{90}Sr; this radionuclide has received special attention for the determination of the intake function. The details of the derivation of the ^{90}Sr-intake function have been discussed by Kozheurov and Degteva (1994). Basically, inference of the intake function is based upon beta-ray measurements of teeth surfaces of residents of villages on the Techa River. Data for the residents of Muslyumovo Village are used as a reference, because this village has a significant population of 3000 persons and has been investigated in most detail due to the fact that it is the most contaminated of the unevacuated villages. Table 6 exemplifies the levels of ^{90}Sr intake for the adult (those born prior to 1940) and children's cohorts of residents of the reference settlement Muslyumovo on the Techa River.

To reconstruct ^{90}Sr intake for other settlements, it was assumed that the ratio of median intake to the median intake at Muslyumovo is equal to the ratio of the median age-standardized ^{90}Sr contents in the skeleton (by statistical analysis of WBC data) for the investigated settlement relative to Muslyumovo. As can be noted, the relative levels of intake depend on the distance from the site of release and the main sources of drinking-water supply (Table 7).

Age-dependent mean-annual-intake levels for ^{137}Cs and short-lived radionuclides were calculated on the basis of the following assumptions. Because most of the ingestion of radionuclides occurred with the consumption of river water in 1950–1952, intakes of ^{137}Cs and short-lived radionuclides were derived from estimates of age-dependent intakes of ^{90}Sr scaled in terms of radionuclide composition of the river water. The ratios of radionuclide concentrations to ^{90}Sr as functions of calendar year and distance downstream from the site of release were calculated using the Techa River Model described in Vorobiova and Degteva (1999). The TRDS database contains age-dependent median-annual-intake levels of ^{89}Sr, ^{90}Sr, ^{95}Zr, ^{95}Nb, ^{103}Ru, ^{106}Ru, ^{137}Cs, and ^{141,144}Ce (Table 8).

Table 6. Example values of annual ^{90}Sr intakes for different age cohorts of residents of the reference settlement Muslyumovo on the Techa River.

Calendar year	Intake of ^{90}Sr for members of the following birth (by calendar year) cohorts, Bq y^{-1}					
	≤1940	1945	1946	1947	1948	1949
1950	2.08×10^{6}	1.37×10^{6}	1.19×10^{6}	9.78×10^{5}	7.50×10^{5}	4.99×10^{5}
1951	4.70×10^{5}	3.76×10^{5}	3.41×10^{5}	3.07×10^{5}	2.68×10^{5}	2.21×10^{5}
1952	4.62×10^{5}	4.15×10^{5}	3.93×10^{5}	3.66×10^{5}	3.39×10^{5}	3.10×10^{5}
1953	8.61×10^{4}	8.30×10^{4}	8.02×10^{4}	7.75×10^{4}	7.39×10^{4}	7.11×10^{4}
1954	1.92×10^{4}	1.91×10^{4}	1.89×10^{4}	1.85×10^{4}	1.82×10^{4}	1.77×10^{4}
1955	1.38×10^{4}	1.38×10^{4}	1.38×10^{4}	1.38×10^{4}	1.38×10^{4}	1.38×10^{4}
1956	6.90×10^{3}	6.90×10^{3}	6.90×10^{3}	6.90×10^{3}	6.90×10^{3}	6.90×10^{3}
1957	5.88×10^{3}	5.88×10^{3}	5.88×10^{3}	5.88×10^{3}	5.88×10^{3}	5.88×10^{3}
1958	4.93×10^{3}	4.93×10^{3}	4.93×10^{3}	4.93×10^{3}	4.93×10^{3}	4.93×10^{3}
1959	3.39×10^{3}	3.39×10^{3}	3.39×10^{3}	3.39×10^{3}	3.39×10^{3}	3.39×10^{3}

Table 7. Relative annual ^{90}Sr intake (relative to Muslyumovo) for several settlements.

Settlement	Distance from the site of release, km	Main sources of drinking water	Location factor f_L
Metlino	7	Techa River and wells	0.52
Asanovo	33	Techa River and wells	0.51
Nadyrov Most	48	Wells and Techa River	0.17
Ibragimovo	54	Techa River	1.3
Isaevo	60	Techa River and wells	0.53
Muslyumovo	78	Techa River	0.93
Kurmanovo	88	Techa River	0.58
Brodokalmak	109	Wells and Techa River	0.14
Russkaya Techa	138	Wells and Techa River	0.19
N. Petropavlovskoye	148	Techa River and wells	0.46
Lobanovo	163	Techa River and wells	0.26
Anchugovo	174	Techa River and wells	0.35
V. Techa	176	Techa River and wells	0.39
Pershinskoye	212	Wells and Techa River	0.16
Klyuchevskoye	223	Wells and Techa River	0.10
Zatechenskoye	237	Techa River and wells	0.20

To the extent possible, dose-conversion factors for internal exposure ($DF_{r,o,Y\text{-}y}$) have been based upon ICRP Publication 67 (ICRP 1993). An exception to this is made for ^{90}Sr, which is the major dose-forming nuclide for the Techa River residents and has been under special investigation. ^{90}Sr-body burdens and tooth-beta counts have been measured for about half of the ETRC members (including all age groups, all villages, and long time periods after the onset of contamination). This database provides an objective basis for the development and validation of biokinetic models. As demonstrated in Tolstykh et al. (2000a,b) the ICRP-67 biokinetic model for strontium is inconsistent with the detailed and long-term results of our study of the Techa River residents. Therefore, for the calculation of dose-conversion factors (exemplified in Table 9) for $^{89,90}Sr$ the biokinetic model developed on the basis of Techa River data is used.

The structure of the TRDS code is demonstrated in Fig. 3. As illustrated, the first step is checking and filtering of residence-history data by comparison with the roster of the communities on the Techa River. Then, individualized internal and external doses are calculated on the basis of age and personal residence-history information. Output data include organ doses for each calendar year for each member of the ETRC.

Table 8. Relative intake of radionuclides at various distances from the site of release (values relative to corresponding ^{90}Sr intake). Examples are shown for the years of major intake.

Settlement	Calendar years	Radionuclide intake relative to local ^{90}Sr						
		^{89}Sr	^{95}Zr	^{95}Nb	^{103}Ru	^{106}Ru	^{137}Cs	^{144}Ce
Metlino	1950–1951	7.1×10^{-1}	2.0×10^{-1}	4.0×10^{-1}	1.7×10^{-1}	8.0×10^{-1}	1.4	6.2×10^{-2}
(7 km)	1952	4.9×10^{-3}	4.0×10^{-3}	5.0×10^{-3}	2.9×10^{-4}	4.1×10^{-1}	1.4	2.7×10^{-2}
	1953	3.4×10^{-5}	8.0×10^{-5}	9.6×10^{-5}	4.8×10^{-7}	2.1×10^{-1}	1.4	1.1×10^{-2}
Muslyumovo	1950–1951	6.8×10^{-1}	7.8×10^{-2}	2.1×10^{-1}	1.3×10^{-1}	6.4×10^{-1}	2.8×10^{-1}	3.2×10^{-2}
(78 km)	1952	4.7×10^{-3}	1.6×10^{-3}	2.0×10^{-3}	2.2×10^{-4}	3.3×10^{-1}	2.8×10^{-1}	1.3×10^{-2}
	1953	3.2×10^{-5}	3.1×10^{-5}	3.7×10^{-5}	3.7×10^{-7}	1.7×10^{-1}	2.8×10^{-1}	5.7×10^{-3}
Brodokalmak	1950–1951	6.7×10^{-1}	5.2×10^{-2}	1.6×10^{-1}	1.2×10^{-1}	5.8×10^{-1}	1.4×10^{-1}	2.4×10^{-2}
(109 km)	1952	4.6×10^{-3}	1.0×10^{-3}	1.3×10^{-3}	2.0×10^{-4}	3.0×10^{-1}	1.4×10^{-1}	1.0×10^{-2}
	1953	3.2×10^{-5}	2.0×10^{-5}	2.5×10^{-5}	3.3×10^{-7}	1.5×10^{-1}	1.4×10^{-1}	4.3×10^{-3}
Zatechenskoye	1950–1951	6.3×10^{-1}	9.4×10^{-3}	4.7×10^{-2}	7.3×10^{-2}	3.9×10^{-1}	7.6×10^{-3}	6.9×10^{-3}
(237 km)	1952	4.3×10^{-3}	1.9×10^{-4}	2.5×10^{-4}	1.2×10^{-4}	2.0×10^{-1}	7.6×10^{-3}	2.9×10^{-3}
	1953	3.0×10^{-5}	3.7×10^{-6}	4.5×10^{-6}	2.0×10^{-7}	1.0×10^{-1}	7.6×10^{-3}	1.2×10^{-3}

Table 9. Red bone marrow (RBM) dose-conversion factors (Gy Bq^{-1}) for the ingestion of ^{90}Sr.

Time (*Y-y*) since Intake, years	Age at intake, years				
	1	5	15	20	30
1	1.83×10^{-7}	8.04×10^{-8}	6.25×10^{-8}	4.00×10^{-8}	3.49×10^{-8}
2	2.59×10^{-7}	1.27×10^{-7}	1.07×10^{-7}	6.75×10^{-8}	5.84×10^{-8}
3	3.09×10^{-7}	1.59×10^{-7}	1.42×10^{-7}	8.99×10^{-8}	7.74×10^{-8}
4	3.45×10^{-7}	1.83×10^{-7}	1.72×10^{-7}	1.09×10^{-7}	9.34×10^{-8}
5	3.72×10^{-7}	2.01×10^{-7}	1.98×10^{-7}	1.25×10^{-7}	1.07×10^{-7}
10	4.33×10^{-7}	2.40×10^{-7}	2.88×10^{-7}	1.79×10^{-7}	1.52×10^{-7}
20	4.53×10^{-7}	2.60×10^{-7}	3.69×10^{-7}	2.23×10^{-7}	1.89×10^{-7}
30	4.58×10^{-7}	2.66×10^{-7}	3.99×10^{-7}	2.38×10^{-7}	2.00×10^{-7}
40	4.60×10^{-7}	2.69×10^{-7}	4.12×10^{-7}	2.44×10^{-7}	2.04×10^{-7}
50	4.61×10^{-7}	2.71×10^{-7}	4.18×10^{-7}	2.46×10^{-7}	2.06×10^{-7}

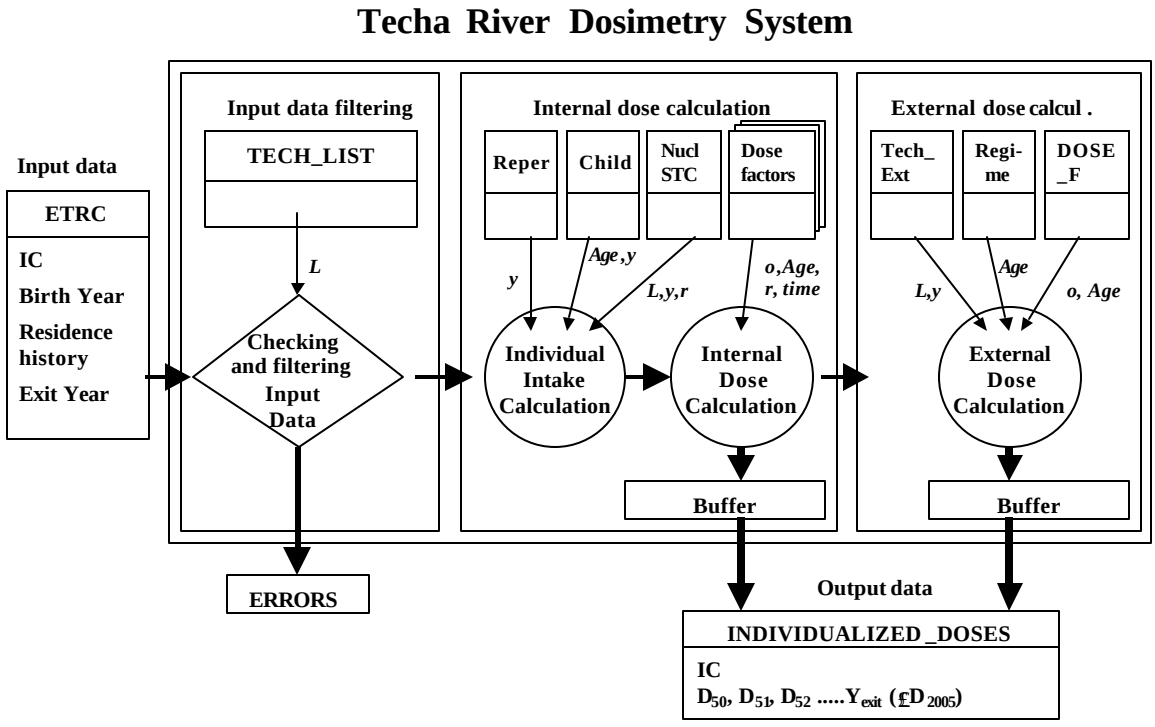


Fig. 3. Schematic diagram of the Techa River Dosimetry System-2000 code.

3.3. EXAMPLE CASE HISTORIES

To illustrate the process of dose calculation, initial data and TRDS results for two cases in the ETRC are presented and discussed. A summary of pertinent information, obtained from URCRM database MAN (described in Degteva et al. 1996c) for these cases, is shown in Table 10. Both example persons lived on the Techa River for their entire lives. Calculations of lifetime external and internal dose to the RBM are presented in Tables 11 and 12.

Table 11 illustrates the calculation of external dose for Case 1. This person was exposed in Metlino during five years (1950–1954) plus two months of 1955 before death in. According to his age at exposure, his behavioral factors (T_1, T_2, *and* T_3) correspond to the last line of Table 4, and the organ-dose factor, A_0 , is taken from the last column of Table 5. Because the range of attained age for this case belongs to a single category (>60 years) during 1950–1955, these factors do not change during the period of exposure. Annual and cumulative RBM doses from external sources are shown in the last column.

Table 12 illustrates the calculation of internal dose due to ^{90}Sr intake for Case 2. The individual calculational endpoint for this case is 1994. This person changed his place of residence in 1953; his levels of intake are calculated by multiplying f_L, $M_{y,L}$ and reference annual intake for his age group I_R^{Sr90} (first column of Table 6). Dose-conversion factors corresponding to the age at intake and time interval between the year of intake and the calculational endpoint are shown in column 9, cumulative doses from annual intakes and total RBM doses due to ^{90}Sr intake are shown in the last column.

Table 10. Case-history data for the two example cases for which results are presented in Tables 11 and 12.

Information	Case 1	Case 2
Identification code	611	65737
Date of birth	1881	4 June 1928
Sex	Male	Male
Residence history	Metlino: 1881–Feb. 1955	Ibragimovo: June 1928–June 1953
		Muslyumovo: June 1953–Dec. 1994
Vital status	Died	Died
Date of vital status	7 February 1955	4 December 1994

Table 11. Calculated external dose to the red bone marrow (RBM) for Case 1. Case-history data are provided in Table 10.

Year of exposure	Location	$M_{y,L}$	Age, years	$D_{Riv,L,y}$, Gy y^{-1}	$D_{Out,L,y}$, mGy y^{-1}	$D_{In,L,y}$, mGy y^{-1}	T_1	T_2	T_3	A_0	RBM dose, Gy
1950	Metlino	1	69	2.72	27.2	12.2	0.017	0.284	0.699	0.73	0.045
1951	Metlino	1	70	12.0	120	54.0	0.017	0.284	0.699	0.73	0.203
1952	Metlino	1	71	4.12	41.2	18.5	0.017	0.284	0.699	0.73	0.069
1953	Metlino	1	72	4.07	40.7	18.3	0.017	0.284	0.699	0.73	0.068
1954	Metlino	1	73	2.19	21.9	9.86	0.017	0.284	0.699	0.73	0.036
1955	Metlino	0.17	74	0.70	7.0	3.15	0.017	0.284	0.699	0.73	0.001
									Total dose		0.42

Table 12. Calculated internal dose to the red bone marrow (RBM) for Case 2. Case-history data are provided in Table 10.

Year of intake	Location	Location factor, f_L	Reference ^{90}Sr intake, Bq y^{-1}	$M_{y,L}$	Individual ^{90}Sr intake, Bq y^{-1}	Age at intake, years	Time since intake, years	$DF_{r,o,Y-y}$, Gy Bq^{-1}	RBM dose, Gy
1950	Ibragimovo	1.26	2.08×10^6	1	2.62×10^6	22	44	2.44×10^{-7}	6.39×10^{-1}
1951	Ibragimovo	1.26	4.70×10^5	1	5.92×10^5	23	43	2.41×10^{-7}	1.43×10^{-1}
1952	Ibragimovo	1.26	4.62×10^5	1	5.82×10^5	24	42	2.33×10^{-7}	1.36×10^{-1}
1953	Ibragimovo	1.26	8.61×10^4	0.5	9.43×10^4	25	41	2.25×10^{-7}	2.12×10^{-2}
	Muslyumovo	0.93		0.5					
1954	Muslyumovo	0.93	1.92×10^4	1	1.79×10^4	26	40	2.18×10^{-7}	3.89×10^{-3}
1955	Muslyumovo	0.93	1.38×10^4	1	1.28×10^4	27	39	2.13×10^{-7}	2.73×10^{-3}
1956	Muslyumovo	0.93	6.90×10^3	1	6.42×10^3	28	38	2.10×10^{-7}	1.35×10^{-3}
1957	Muslyumovo	0.93	5.88×10^3	1	5.47×10^3	29	37	2.07×10^{-7}	1.13×10^{-3}
1958	Muslyumovo	0.93	4.93×10^3	1	4.58×10^3	30	36	2.04×10^{-7}	9.35×10^{-4}
1959	Muslyumovo	0.93	3.39×10^3	1	3.15×10^3	31	35	2.02×10^{-7}	6.37×10^{-4}
							Total dose		0.95

3.4. DOSIMETRIC DATA AVAILABLE FOR RISK ANALYSIS

Calculated results of dose for members of the ETRC are contained in database INDIVIDUALIZED DOSES located on the URCRM central server. This database is the responsibility of the URCRM Biophysics Laboratory and is available to the epidemiologists involved in risk assessment. All doses to be provided in the database are for absorbed doses with no radiation- or tissue-weighting factors applied (possible doses from ingested alpha-emitting radionuclides are believed to be insignificant and are not considered). A unique identifier (IC) for each ETRC member is provided. This IC can be used to link dosimetric data to epidemiologic data on diagnoses as well as date of birth, sex, ethnicity, residence history, and date of vital status determination or any other information from database MAN.

The organs for which doses are calculated are the following: red bone marrow, bone surface, stomach wall, small intestinal wall, upper large intestinal wall, lower large intestinal wall, testes, ovaries and uterus. It is possible to include in this list other organs for which dose factors have been tabulated by the ICRP. In general, the criterion for the calculation of dose to a specific organ is whether the dose to that organ is significantly different from the average dose to the other organs.

Cumulative doses are provided for each person on a year-by-year basis starting from the first year of exposure (1950 for those who lived on the Techa River at the onset of contamination or the year of migration to Techa Riverside communities). The calculational endpoint, *Y*, can vary according to the analyst's wishes; for a particular individual it might be the year of death, the year of exit from the cohort due to migration, the year of vital status determination, or the date of "fixing" the cohort for analysis. *Y* could also be any or all of the above minus some presumed latent period for cancer induction. Also, it is possible to perform specific calculations, if desired by the analyst; for example, to examine the association of risk with only external dose or only internal dose from one or more radionuclides.

4. ANALYSIS OF REVISED DOSES

The first version of the dosimetry system (TRDS-96) was developed at the URCRM within the framework of a contract with the Federal Department of the Russian Ministry of Health (Degteva et al. 1996e). TRDS-96 included intake levels for only ^{89}Sr, ^{90}Sr and ^{137}Cs for the calculation of internal dose and simplifying assumptions (discussed below) were used for the calculation of external dose. Comparisons of TRDS-96-based dose assessments with preliminary values calculated using the new version of the system (TRDS-2000, which is discussed in this paper) demonstrate the improvements in dose reconstruction obtained in the framework of this JCCRER Project. All calculations are performed for the 1996 freeze of the ETRC in order to demonstrate the changes connected only with the new methodology of dose assessment. Dose distributions for the next freeze of the ETRC (2000) will be calculated on the basis of improved individual data after these data have been provided by the URCRM Registry Department. The improvements in follow up data will introduce only minor changes in dose distributions; these changes will be due to the verification of individual-residence histories and/or information on birth dates and vital status for some portion of ETRC members.

4.1. INTERNAL DOSES

As described above, internal doses for members of the ETRC are calculated on the basis of age- and location-specific mean-annual-intake levels of radionuclides, age-dependent biokinetic models for radionuclides, and individual-residence histories for each subject. Fig. 4 presents the distributions of internal dose in red bone marrow (RBM) and bone surface (BS) among the members of the ETRC. As seen, more than half of the people have internal RBM doses between 0.1 and 0.5 Gy. Absorbed doses in cells on bone surfaces (BS) have the same distributions as do the RBM doses, but the values are about two times higher. As most of these doses are due to ^{90}Sr, the new (TRDS-2000) values are not greatly different from the old (TRDS-1996) values. However, two changes have been made. The first is that the new doses include contribution from additional radionuclides, which increases the calculated doses. The second change is that the statistical evaluation of the distribution ^{90}Sr doses (Degteva et al. 1999) has led to the use of a median value for the individual-to-model ratios rather than the arithmetic mean value used previously. This has decreased the calculated estimates of dose.

Fig. 5 demonstrates the distributions of dose to the LLI and ULI among members of the ETRC. Comparison of the old (TRDS-1996) and new (TRDS-2000) values shows that the inclusion of short-lived radionuclides results in a threefold increase in dose for the upper Techa River residents: Maximal values become 0.98 Gy instead of 0.38 Gy for the LLI and 0.34 Gy instead of 0.12 Gy for the ULI. The old TRDS approach gave an average value of absorbed dose for all tissues except RBM, BS, ULI and LLI walls, because only ^{137}Cs, which has uniform distribution throughout the body, was taken into account. The levels of internal dose for other soft tissues were lower than 0.047 Gy for all members of the ETRC and lower than 0.02 Gy for 95% of people. The new TRDS approach allows the separate consideration of other parts of the gastrointestinal tract (small intestine and stomach), which have elevated exposure due to the ingestion of radionuclides with low gastrointestinal absorption (such as ^{95}Zr, ^{95}Nb, ^{144}Ce, etc.). The new calculation shows that the dose to the small intestine of the upper Techa River residents increases by 50% and reaches a value of 0.07 Gy. As for the stomach, testes, ovaries, and uterus, the inclusion of short-lived radionuclides results in an increase of less than 10% in absorbed dose for the upper Techa River residents. The distributions of dose for these tissues are very similar: The maximum level is 0.05 Gy and about 90% of people have doses lower than 0.02 Gy. The primary radionuclide contributing to internal dose in these tissues (as well as for other tissues not considered separately) is ^{137}Cs.

4.2. EXTERNAL DOSES

The results of calculations of external dose have shown that the new assessments are significantly lower than the external doses evaluated in 1990 and published in 1994 (Degteva et al. 1994). Fig. 6 shows the distributions of the “old” and the “new” external doses for permanent residents of villages along the Techa River (those who lived at the same location during the entire period of the releases). The causes of the substantial decrease in the estimates of external doses are the following.

First, in the absence of exposure-rate measurements along the entire river in the early period, the following assumptions were made for the old calculations:

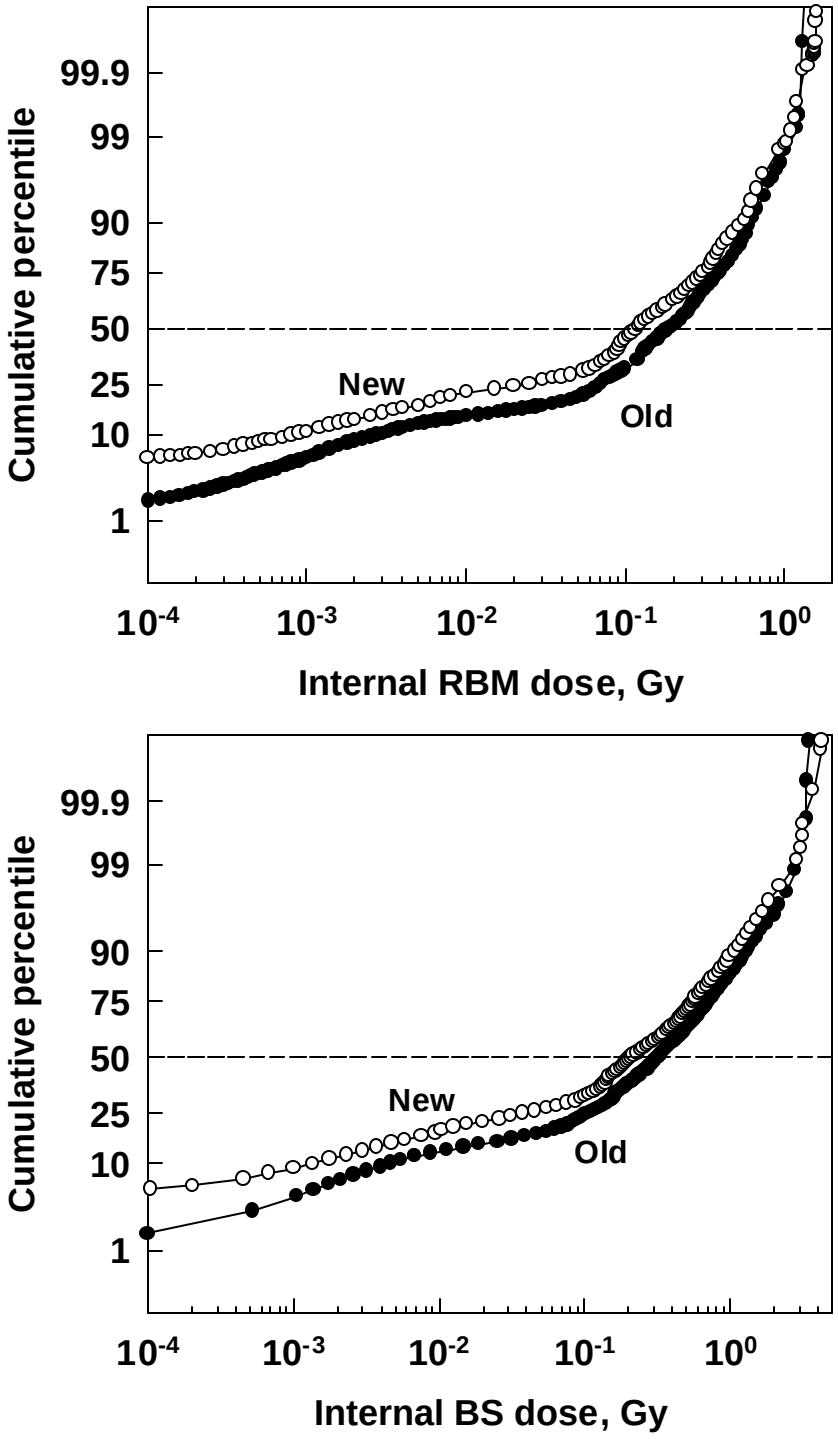


*Fig. 4. Distribution of doses to **upper)** the red bone marrow (RBM) and **lower)** the bone surface from ingestion of radionuclides for members of the ETRC.*

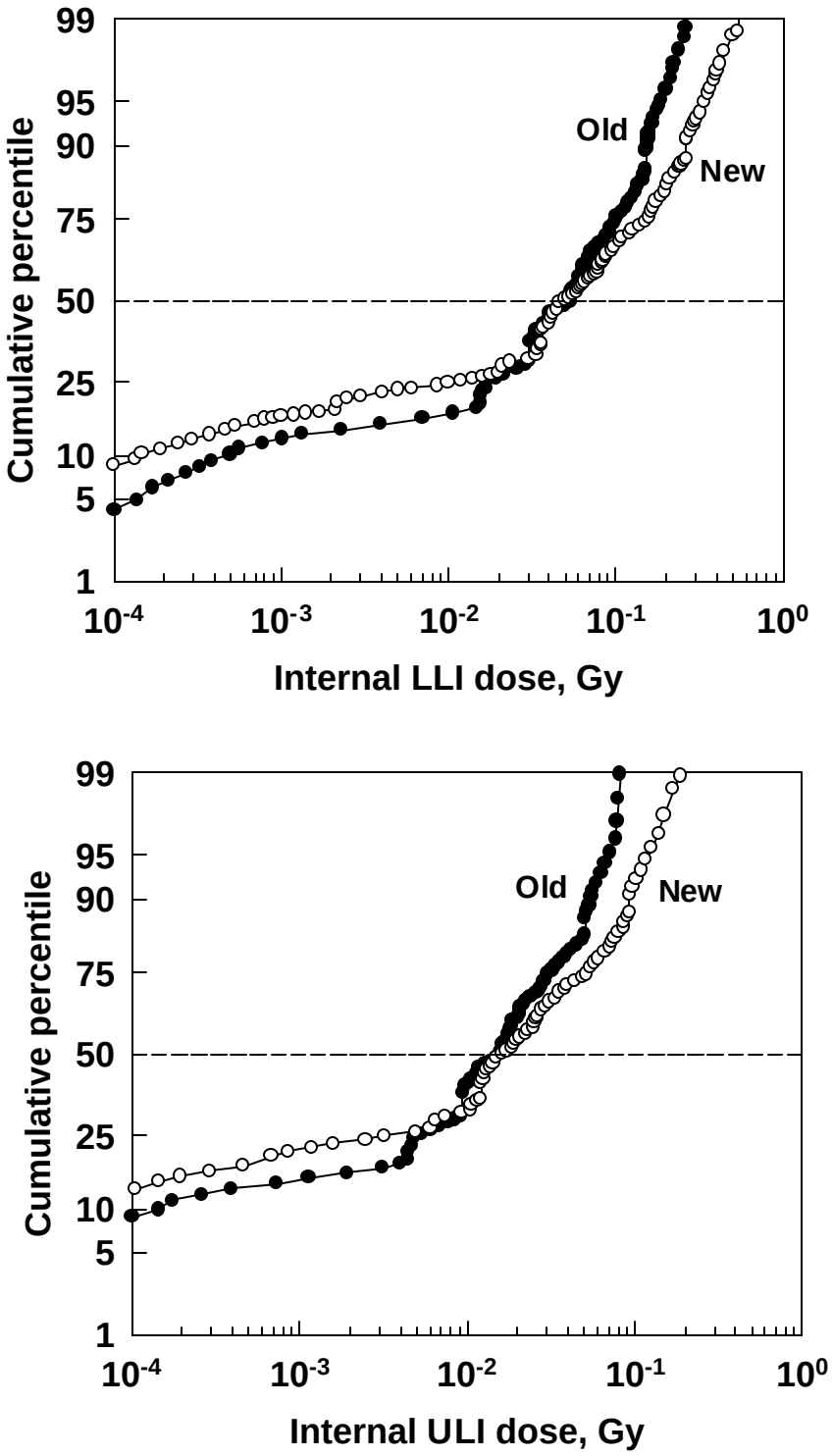


*Fig. 5. Distributions of "old" and "new" doses to **upper)** the lower large intestinal (LLI)wall and **lower)** the upper large intestinal (ULI) wall. The new doses tend to be higher due to the inclusion of additional short-lived radionuclides in the analysis.*

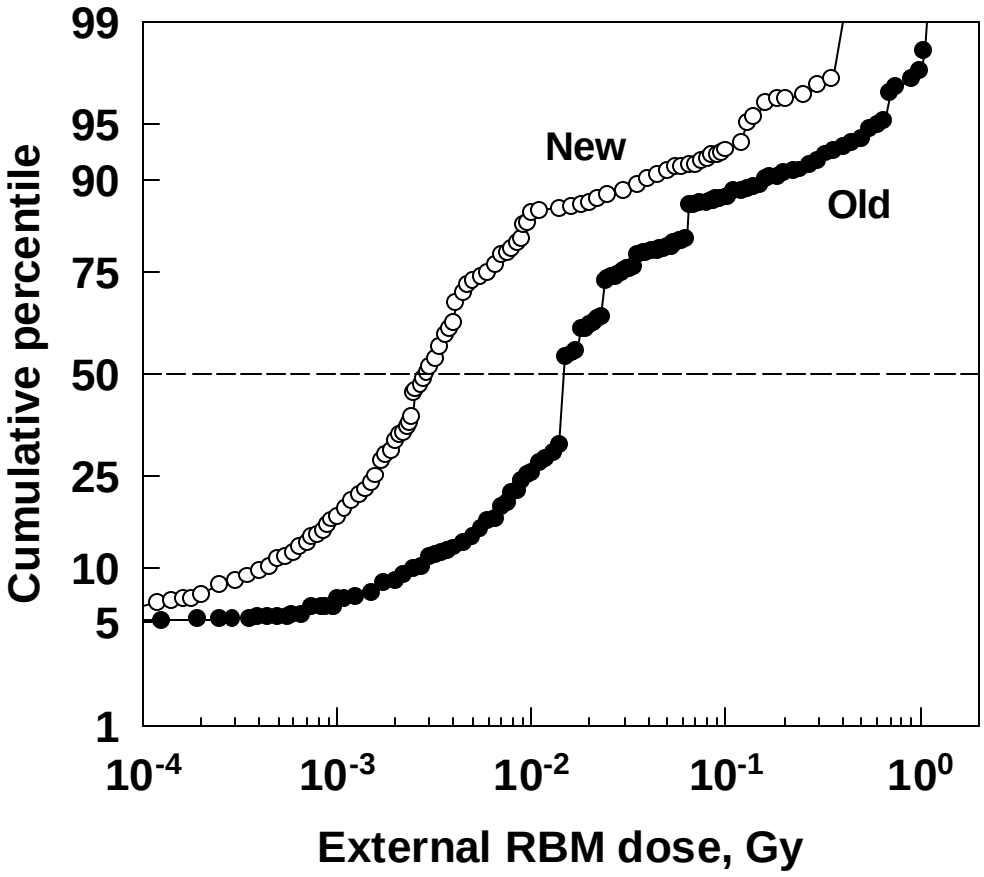


Fig. 6. Distributions of estimates of external dose for the "old" and "new" calculations. The new estimates are substantially less than the old estimates.

- The decrease of exposure rate with downstream distance in 1951 was the same as was the decrease of concentration of beta-emitting radionuclides in river water (exposure rates measured in 1951 near the site of release were used as the "starting points"); and
- The levels of external exposure rates were the same in 1951 and 1950, because annual levels of released activity were approximately the same in these two years.

The analysis of historical monitoring data and the modeling of radionuclide transport in river water and bottom sediments has shown that both of these assumptions result in significant overestimates of external doses, because the decrease of exposure rate with distance was significantly greater than was the decrease in concentrations of radionuclides in water, and the amount of activity accumulated in bottom sediments in 1951 was significantly higher than in 1950 (Vorobiova et al. 1997). Thus, the development of the Techa River model and the more in-depth analysis of historical monitoring data have led to more appropriately modeled values of absorbed dose in air for the important years of 1950 and 1951.

Second, dose rates within residence areas were assumed in the old calculations to be the same for an entire settlement and were based on the first line of households (closest to the riverbank). This assumption was another cause of overestimation of external doses for those who lived in houses located farther from the riverbank. The study of the variations in gamma-exposure rate within residence areas as a function of distance from the river (Vorobiova et al. 1999a) has led to an evaluation of the ranges of exposure rate within residence areas and the calculation of weighted-average values for each settlement.

Third, as described in Vorobiova et al. (1999a) and Degteva et al. (2000c), the behavioral factors used in the old dose assessments had been evaluated for critical groups for radiation-protection purposes. These old assumptions resulted in overestimation of the time that the average person spent near the shoreline, where the external exposure rates were the highest. New evaluations are now used in the revised model; these revised evaluations are also comparable with two other independent, recent studies (Vorobiova et al. 1999a; Degteva et al. 2000c).

The distributions of total dose accumulated through 1990 for about 30,000 members of the ETRC are shown in Table 13. The majority of persons received soft tissue doses within the range of 1–10 mGy, 10–100 mGy for the colon and 100–1000 mGy for the red bone marrow and bone surface. The maximum dose was 4.4 Gy to the bone surface.

5. QUALITY ASSURANCE

Much of the work accomplished as the main part of this project is of the nature of quality control/quality assurance. The models and databases used in TRDS-2000 have been validated by comparison with experimental data (as discussed below). One of the primary aspects of the overall project has been the recalibration of the URCRM whole-body bremsstrahlung counter (WBC), which is a critical component of the study in terms of providing primary data for the internal dose reconstruction. The situation for this dose-reconstruction effort is highly unusual in that about half of the individuals making up the ETRC have been counted at least once in the unique URCRM WBC; thus, the body burdens of the most significant (in terms of dose) radionuclide ^{90}Sr have been measured directly. The ^{90}Sr-body burdens measured for the TRC members have been used for the development of the age-dependent strontium metabolic model (this model has been utilized to produce TRDS-2000 databases SR90 and SR89) and for the reconstruction of the relative ^{90}Sr intakes for the Techa Riverside settlements (TRDS-2000 database NUCL_STC).

5.1. WHOLE-BODY COUNTER RECALIBRATION AND MODIFICATION

The data set of whole-body counter measurements (part of database MAN) is critical to the success of efforts to provide individual doses. The URCRM whole-body counter (WBC), which is identified as SICH-9.1, has been used since 1974 to measure ^{90}Sr, ^{137}Cs and ^{40}K in people (Kozheurov 1994). The measurements of ^{90}Sr were achieved by measuring with a phoswich detector the bremsstrahlung of ^{90}Y (daughter of ^{90}Sr with a half-life of 64 h) beta rays; for this purpose scanning-bed geometry enclosed in a special shielding room was used (Kozheurov 1994). Analyses of ^{137}Cs and ^{40}K were accomplished at the same time with the same detector by the measurement"of their photopeaks (photons with energy ranges

Table 13. Distribution of total dose accumulated through 1990 for about 30,000 members of the ETRC. The upper part of the table gives the distributions of dose by percentiles of the total dose. The lower part of the table gives the percentage of the population within several dose ranges. Highlighted values indicate the dose range received by the majority of the population.

Total dose, Gy:

Organ	10%	25%	50%	75%	90%	Maximal
Red bone marrow	0.0017	0.029	0.12	0.34	0.63	1.7
Bone surface	0.0028	0.047	0.22	0.62	1.2	4.4
Lower large intestinal wall	0.00088	0.017	0.054	0.16	0.33	0.92
Upper large intestinal wall	0.00069	0.0075	0.021	0.060	0.16	0.54
Small intestinal wall	0.00055	0.0026	0.0056	0.017	0.048	0.42
Stomach wall	0.00056	0.0024	0.0045	0.014	0.046	0.44
Testes	0.00064	0.0024	0.0043	0.014	0.052	0.52
Ovaries	0.0005	0.0021	0.0037	0.013	0.044	0.41
Uterus	0.0005	0.0021	0.0036	0.012	0.044	0.41

Percent of population:

Organ	≤1 mGy	1–10 mGy	10–100 mGy	100 mGy–1 Gy	>1 Gy
Red bone marrow	7.9	12	23	55	1.7
Bone surface	9.0	9.5	13	57	11
Lower large intestinal wall	11	12	44	34	-
Upper large intestinal wall	12	16	54	18	-
Small intestinal wall	14	56	22	7.7	-
Stomach wall	14	58	20	7.6	-
Testes	13	59	20	8.2	-
Ovaries	16	58	20	7.1	-
Uterus	15	58	20	7.1	-

620–740 keV and 1400-1580 keV, respectively). For the original calibration of the WBC in 1973, two surrogate-human structures of limited useful life were used. More than 30,000 measurements were carried out during the following 25-year period on more than 15,000 people. The minimal detectable ^{90}Sr activity was evaluated as 1.85 kBq; the maximal activity measured for an individual of the TRC was 230 kBq.

It must be noted that an extensive autopsy program has been under way at URCRM during the same period (Tolstykh et al. 1998; Degteva et al. 1998). This autopsy program included the radiochemical measurements of ^{90}Sr in bone samples from autopsies of Urals residents. This autopsy program was reduced only after a sufficient number of ETRC members were measured *in vivo* with the WBC and their ^{90}Sr-body-burdens, derived from WBC measurements, were validated by the results of the analysis of *post mortem* samples (Tolstykh et al. 1998; Degteva et al. 1998). The consistency of these two methods was confirmed, and this serves as a major quality-assurance check for the critically important WBC data.

In addition, to validate the WBC data set, the measurement system was once again calibrated in 1998 using a specially constructed anthropomorphic phantom that contains ^{90}Sr distributed through simulated bones and another set of phantoms containing ^{40}K and ^{137}Cs (Kozheurov et al. 1998). The strontium phantom (FST-06T) is shaped as an anatomical model of ICRP Reference Man (ICRP 1975). The phantom contains an activity of 44±2 kBq of ^{90}Sr (plus an equal amount of its daughter ^{90}Y) uniformly distributed in the skeleton mass. The design of this phantom has been discussed at the Workshop "In vivo measurements of internal contamination: New techniques for new needs" in 25–28 May, 1999, Mol, Belgium, and described in detail by Kovtun et al. (2000).

In general, the calibration factors obtained in 1973 and in 1998 agree quite well—the more important ones are within a few percent and all factors agree within 16% (Kozheurov et al. 1998). The spectrum of bremsstrahlung radiation of ^{90}Sr-^{90}Y obtained by measuring the FST-06T phantom with whole-body counter SICH-9.1 is presented in Fig. 7a (the duration of the measurement is 980 min.). For comparison, an analogous spectrum from a real person who lived on the Techa Riverside (IC 66375, male aged 57; with body burden of 12 ±2 kBq of ^{90}Sr; the duration of measurement is 80 min) is presented in Fig. 7b. Figs. 7 (a, b) demonstrate that the bremsstrahlung production and the spectrum from the phantom is comparable to that from a real human and of the same shape. The results of the repeated calibration with the FST-06T phantom once again confirmed the reliability and credibility of the data set of multiple WBC measurements.

The condition in 1998 of the original SICH-9.1 detectors and electronic equipment was poor. In order to provide for the continuation of the individual body-burden monitoring program, a new set of detectors and a new electronic system for spectrum analysis was specified and purchased in the course of the current project. It was decided to use the same shielding room and the same geometry of measurements (scanning-bed), as well as the same type of detectors (phoswich). The University of Utah sent out a request-for-bid package in early 1998. The winning bid was received from "Pribori Oy", an official distributor of EG&G ORTECH, and the

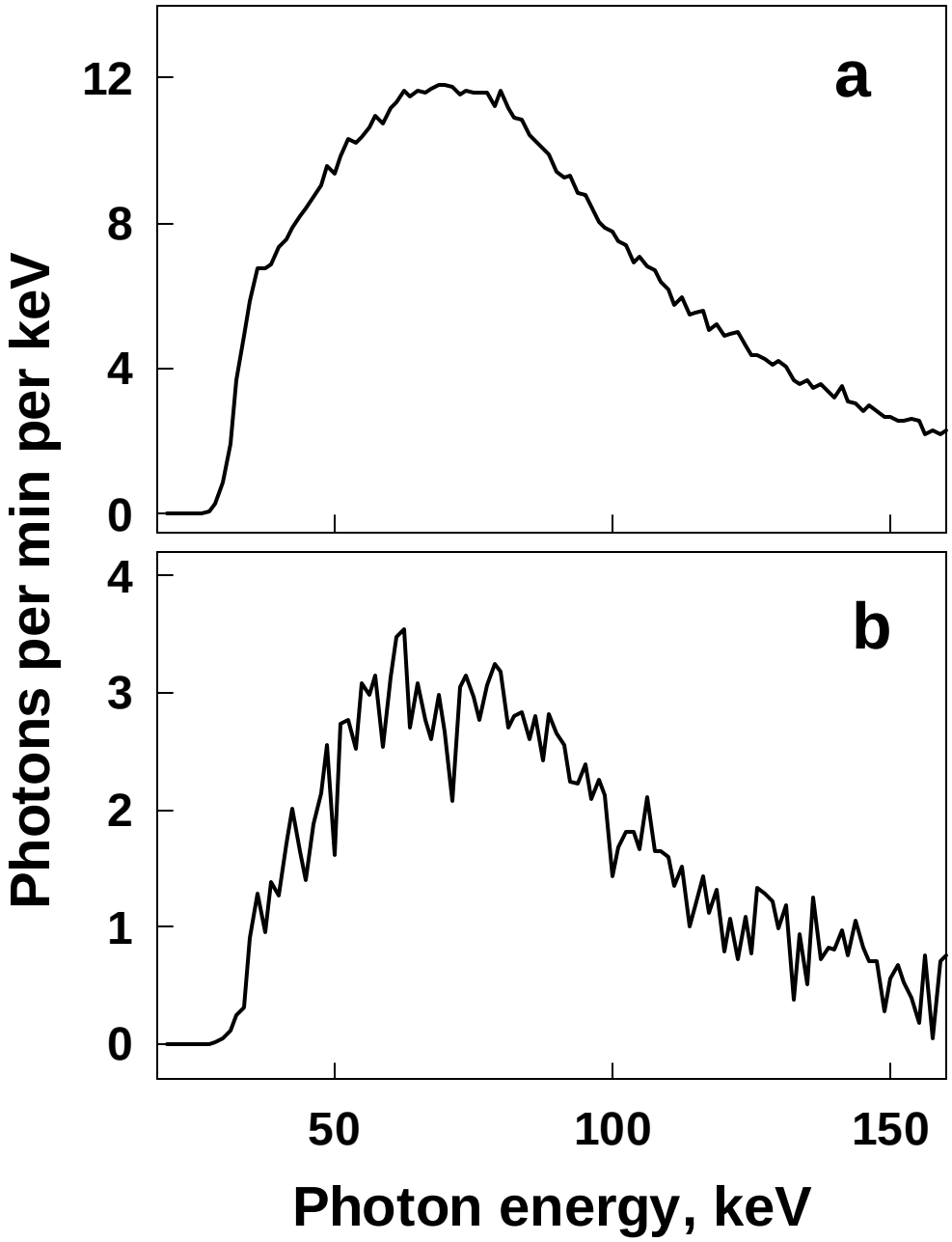


Fig. 7. SICH-9.1 bremsstrahlung spectra of $^{90}Sr/^{90}Y$ obtained from upper) the FST-06T phantom and lower) a real person with 90Sr incorporated in the skeleton.

order was placed in November 1998. This equipment was installed at URCRM by Pribori Oy during July 1999 and has been formally accepted. Fig. 8 demonstrates several views of the new set of equipment, with the FST-06T phantom placed as a "subject" undergoing measurement.

Fig. 8. Several views of the updated whole body counter with the new phantom placed as a "subject" to be measured.

5.2. VALIDATION OF THE STRONTIUM BIOKINETIC MODEL

An age-dependent strontium biokinetic model was elaborated for dose estimation of the residents of the villages along the Techa River (Degteva and Kozheurov 1994). This model takes into account changes in metabolic parameters throughout the entire life of the subject, beginning with bone formation and growth in childhood and including loss of skeletal calcium in old age. Age dependencies for the model parameters were obtained by fits to available data sets of ^{90}Sr measurements in humans. Data with different schedules of intake were used for parameter evaluation: 1) the age dependence of long-term ^{90}Sr-body burdens as measured by the WBC of the residents of Muslyumovo Village on the Techa River in 1976 (Degteva and Kozheurov 1994); 2) United Kingdom (national survey) and United States (New York and San Francisco) data on ^{90}Sr from global fallout as reported by Papworth and Vennart (1984) and Leggett et al. (1982); and 3) experimental data with a single intake of ^{85}Sr to volunteers (Likhtarev et al. 1975).

In order to validate the age-dependent biokinetic model for strontium, model predictions were compared with experimental data other than that used for the evaluation of model parameters (Degteva and Kozheurov 1994; Degteva et al. 1996d). It has been found that model predictions are in reasonable agreement with the measurements of global ^{90}Sr in children's bones from the Glasgow survey (Warren 1972) and also with data from the Czech Republic (Muller 1970). In addition, model calculations were compared with measured levels for adults (autopsy data plus WBC data obtained after 1976) obtained from 40 years of observation on the Techa River (Tolstykh et al. 1998). Fig. 9a demonstrates mean levels for the upper- and mid-Techa region where the measurements were started in 1951, and Fig. 9b shows the measurements for the lower reaches that were started after 1956. Two model curves outline the corridor of values for age cohorts included in the measurements. The consistency of model calculations and measured values is obvious.

In addition, predictions of ^{90}Sr-body burden were performed using URCRM and ICRP67 (ICRP 1993) biokinetic models for the area contaminated as a result of the Chernobyl accident (7–12 years after the accident) and for Muslyumovo Village on the Techa River (30–45 years after the onset of contamination). The comparison of these calculations with the results of actual measurements (autopsy data obtained in 1993–1998 for the Zhitomir Oblast contaminated as a result of the Chernobyl accident and WBC measurements obtained in 1978–1994 for the residents of Muslyumovo) has been described by Tolstykh et al. (2000a). This comparison has demonstrated that both biokinetic models (URCRM and ICRP67) satisfactorily describe the measurements for adults in the case of Chernobyl accident. Applied to other ages, the URCRM model curves are in good agreement with ^{90}Sr-body burdens measured with the SICH-9.1 WBC between 1978 and 1994 for all age cohorts of the Muslyumovo residents. (Recall that WBC data obtained in 1974–1978 only have been used for model-parameter evaluation.) The ICRP67 model predictions were found to be higher than the WBC data for people aged 10–20 at the onset of intake, and lower by a factor about 1.5–1.8 for children aged 1–5 at the onset of intake (Tolstykh et al. 2000a).

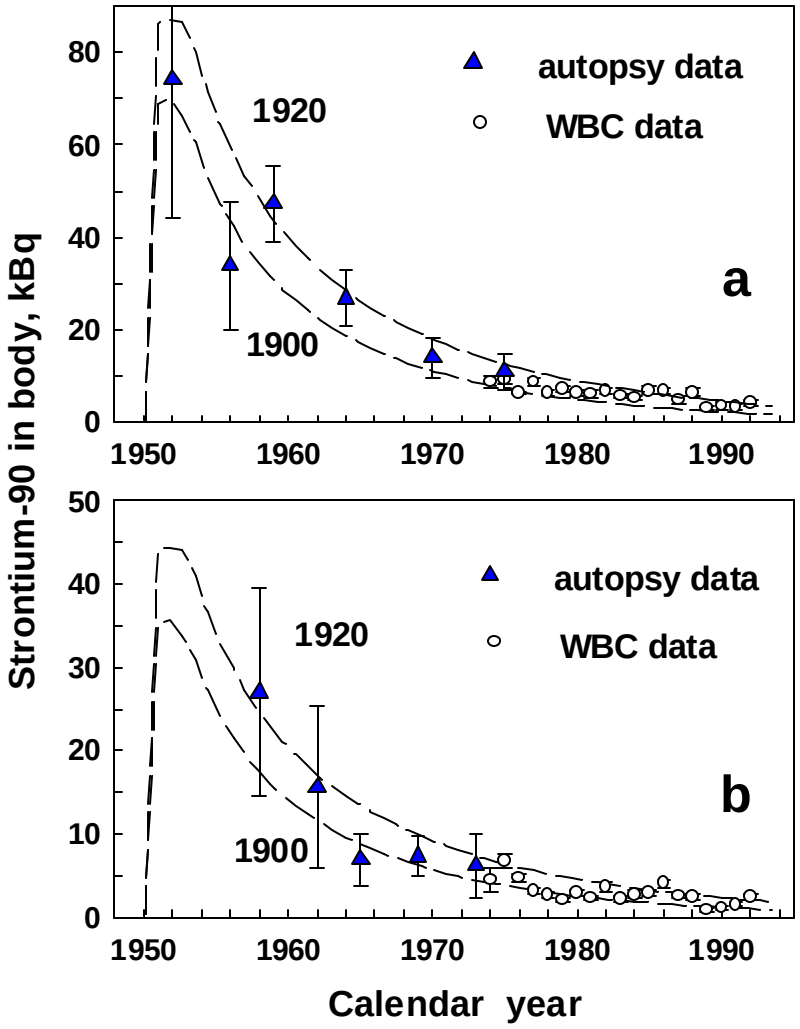


Fig. 9. Mean levels of ^{90}Sr in adult humans for the Techa Riverside settlements (a) up to 80 km from the site of release and (b) for distances of 90–150 km. The model curves outline the corridor of values between age cohorts born in 1900 and 1920.

The consistency between the URCRM strontium biokinetic model calculations and the results of actual measurements in humans of different ages for different schedules of intake and for time periods as long as 45 years after intake assures the reliability of this model used in TRDS-2000 for the calculation of internal doses due to ^{90}Sr.

5.3. VALIDATION OF THE TECHA RIVER MODEL

The Techa River model was developed to reconstruct radionuclide concentrations in water and sediments for the early period of contamination between 1949 and 1951. This model is used in TRDS-2000 for the calculation of relative intakes of ^{137}Cs and short-lived radionuclides (database NUCL_STC) and for the reconstruction of exposure rates on the river bank (database TECH_EXT) for the period 1949–1951, when there were no appropriate measurements.

As demonstrated by Vorobiova and Degteva (1999), this model successfully correlates the rates of releases as reconstructed by the Mayak experts, hydrological data, and available environmental monitoring data. Two data sets have been used to evaluate model parameters:

- Results of experiments on physical modeling of radionuclide behavior in different kinds of artificial reservoirs carried out in 1952–1955 in the Urals; and
- Measurements of specific beta activity in the water of the Techa River along the distance from the site of release for 1951.

Parameter estimates obtained for the Techa River are compatible with values published in the literature for a similar watercourse (Schaeffer 1975). Also, the calculated rates-of-change of ^{90}Sr and ^{137}Cs concentration in water for the period of massive releases are in reasonable agreement with the results of measurements of these long-lived radionuclides performed in the 1960's and 1970's for flood-plain soils extensively contaminated in 1951 (Vorobiova and Degteva 1999). The Techa River model predictions are also validated by experimental data on radionuclide concentration in bottom sediments (these data have not been used for the evaluation of model parameters).

An important result of the modeling was the ability to reconstruct external gamma-dose rates in air near the riverbank. These dose rates were calculated for 1950–1951 on the basis of modeled and measured radionuclide concentrations in bottom sediments using two different methods, and the results showed reasonable agreement each other (Vorobiova and Degteva 1999). The results of analogous calculations performed for 1952 were validated by actual measurements. The close agreement of the values calculated using both approaches and measurement results provides assurance that the levels of river-system contamination in 1949–1950 and the external gamma-dose rates reconstructed using this model are sufficiently reliable.

5.4. POSSIBILITIES FOR THE VALIDATION OF EXTERNAL DOSES

As discussed above, there are important reasons to consider the old calculations of external doses as overestimates. Because of significant reductions in external dose that are due to a variety of factors and because of the substantial uncertainty that is attached to the estimates of external dose, the validation of the new assessments of external dose is now an issue of major importance. The more useful, accepted methods of validation are measurements of luminescence of quartz extracted from bricks and, more importantly, the measurement of dose in teeth of ETRC members through the technique of electron paramagnetic resonance (EPR). These activities were included in our original project, and progress had been made before these activities were cancelled.

The applicability of the use of "natural" solid-state dosimeters, such as quartz (a component of bricks) and hydroxyapatite (a component of tooth and bone tissue) has been investigated within the framework of this JCCRER Project and a separate project for INCO-COPERNICUS (Coordinator is Dr. Peter Jacob, GSF, Germany). Samples of bricks from abandoned buildings located near the Techa shoreline were collected, the quartz was extracted from the bricks, and doses were assessed using the thermoluminescence (TL) method (Bougrov et al. 1998, 1999). Monte Carlo simulations of doses accrued in bricks were performed for the geometries of exposure specific to the sample sites on the basis of the dose rates in air near the shoreline as reconstructed with the Techa River model. It was found that the calculated and TL-measured doses in bricks are in reasonable agreement (Bougrov et al. 1999). This study has demonstrated the potential of the luminescence method in combination with Monte Carlo simulations of radiation transport at sampling sites for the validation of environmental doses in the upper and middle Techa region.

A pilot study (Romanyukha et al. 1996a; 1996b) has been performed to measure dose received by teeth as determined by EPR analysis. This pilot study has confirmed the applicability of EPR for retrospective individual-dose evaluation. This method, based upon measurements of samples collected for dental health reasons, also provides the capability for the validation of estimates of uncertainty in assessment of external dose. An analysis of the territorial distribution of living subjects included in the ETRC has been performed to show that it is feasible to arrange a special system for obtaining sufficient numbers of tooth samples for EPR analyses (Degteva et al. 1997). Also, some studies were carried out with the purpose of improving the experimental technique (Romanyukha et al. 1999, 2000; Haskell et al. 2000). Preliminary comparison of individual doses measured by EPR and TRDS-2000-based external dose calculations for several residents of Metlino Village (the upper Techa region) showed reasonable agreement (Degteva et al. 2000d). Also, it has been shown by Tolstykh et al. (2000b) that, for the middle Techa region, EPR doses are comparable with the sum of background dose plus dose from incorporated ^{90}Sr (the latter has been calculated using Monte Carlo simulation of electron transport in tooth tissues). This finding confirms that the external component of total dose for the middle and lower Techa region was relatively low. In general, these studies have demonstrated the potential of EPR methods for the validation of individual external doses for members of the ETRC.

An analysis of stable translocations using the fluorescence in situ hybridization (FISH) method was performed for several residents of villages along the Techa River (Bauchinger et al. 1998). The findings obtained in this study verified that the "old" assessments of external dose were overestimates. Some efforts also were made to improve the technique of statistical treatment of the FISH assay results to provide more correct interpretation of individual results (Anspaugh et al. 2000). The approach suggested could permit use of the FISH method as one of the experimental methods for validation of external doses for the members of the ETRC.

The comparative analysis of the applications of the above three retrospective dosimetry methods (TL, EPR, and FISH) for the first validation of external doses for the Metlino site (Degteva et al. 2000d) indicates that it is feasible to validate TRDS-2000 external dose estimates in the future.

6. TRDS-2000 UNCERTAINTY ASSESSMENT

Examination of the sources and magnitudes of uncertainty in radiation doses to individuals in the ETRC is an important task of the current project. At the present time, the analysis of uncertainties for each of the individual doses estimated by the TRDS model is incomplete, but the source of information for each term in the TRDS-2000 dose equation has been evaluated and the approach for estimating uncertainty has been developed.

6.1. APPROACH TO ESTIMATING UNCERTAINTIES

The TRDS-2000 calculation of uncertainty is based on stochastic application of the basic equation described in Section 3.1. The mean, median, percentiles, and other descriptive parameters of the individuals' radiation doses are calculated using Monte Carlo simulations. The required inputs for these analyses have been developed during the course of Project 1.1. The actual results vary depending on the analysis being undertaken, i.e., the specific individual, the calculational endpoint year *Y*, organ of interest *o*, and route of exposure (internal or external). Example results are presented below.

In the basic equation, the term $M_{y,L}$ comes from individual-life-history information and is a series of constants. All of the other parameter values are either calculated or approximated and have associated uncertainty.

The key radionuclide intake term $I_{Y,r,L}$ has a very complex uncertainty structure (Degteva et al. 1999b). The variation of intake levels within a single village and age cohort depends mainly on the source of drinking-water supply. In the TRDS-2000 system, the village-average WBC-determined body burdens of ^{90}Sr have been used to derive the deterministic estimate of accumulated dose. The village average is derived from the entire distribution of measured body burdens of residents of that village. The relation of the actual measurements to the model predictions is described using Individual-to-Model Ratios (*IMR*) (Degteva et al. 1999b). For a person of age τ at the beginning of intake and who was measured by WBC at the year t_m, the value of *IMR* is determined as the ratio of an individual-body-burden measurement, $A_{ind}(\tau,t_m)$, to the value derived from the reference model (representing a permanent resident adult in Muslyumovo), $A_{mod}(\tau,t_m)$:

$$IMR = A_{ind}(\tau, t_m)\left[A_{\mathrm{mod}}(\tau, t_m)\right]^{-1} .$$

In the case of repeated measurements, the value of *IMR* is determined as the average of all ratios of WBC measurements-to-the respective reference-model values. *IMR*s serve as age- and time-normalized values that permit the analysis of the entire set of individual data on ^{90}Sr in members of the ETRC.

The uncertainty in intake and retention of ^{90}Sr for any one individual within the village is defined by the actual distribution of *IMR* developed for that village (Degteva et al. 1999b). The *IMR* includes all the TRDS-2000 parameters that go into estimation of term $I_{Y,r,L}$, except the location factors f_L. As defined and presented in Degteva et al. (1999b), the *IMR* is the ratio of the measurement for a specific village to the *prediction made as if that individual lived in*

Muslyumovo. Thus, it is necessary to adjust the basic *IMR* to the specific village by dividing it by the factor f_L^{Sr90}, defined in Section 2 as the annual ratio of ^{90}Sr intake for location *L* to ^{90}Sr intake for residents of the reference settlement of Muslyumovo. Thus, the normalized *IMR* is actually the ratio of the actual measurements to the model prediction for the specific location. This normalization provides the appropriate magnitude of the range of uncertainty for the predicted intakes.

The normalized *IMR*'s are time-integrated quantities, in that they reflect the deviation of total lifetime intake and retention from that predicted by the TRDS environmental and exposure models. However, it is reasonable to assume that particular individuals would have similar behavior from one year to the next, and that the inter-annual variation is captured in the total normalized *IMR*. Thus, the distribution of normalized *IMR*'s for each village can be used to estimate the annual distribution of intakes and retentions for residents of that village. Because of these considerations, it is not necessary to model explicitly the various components of drinking-water source, diet, uptake, or metabolism that go into estimation of the radionuclide-intake term $I_{Y,r,L}$; this greatly simplifies the uncertainty analyses. The distribution shape and range of the term $I_{Y,r,L}$ is defined for each village by the village-specific normalized *IMR*'s.

Dose-conversion factors, $DF_{r,o,Y\text{-}y}$, are calculated using biokinetic models, and their uncertainties are determined mainly by the variability of metabolic parameters (Shagina et al. 2000). However, for ^{90}Sr, the individual variability in uptake and metabolism is actually captured in the *IMR* values because the *IMR's* reflect not only intake but also long-term retention. The remaining uncertainties in the dosimetric model are embodied within the specific effective energy quantity and are associated mainly with variations in masses, shapes and locations of the organ and tissue of the human body and with oversimplifications of the representations of certain complex anatomical structures in the body when calculating the energy deposition (NCRP 1998). Thus, the uncertainty in the dose-conversion component for ^{90}Sr is relatively low. For this assessment, this variability has been approximated as a lognormal distribution with a geometric standard deviation of 1.25. The uncertainties in the dose-conversion factors for other radionuclides are larger, reflecting the lack of available measurements and the potential for individual variations in uptake and retention. The values for the dose factors for other radionuclides can be considered as lognormal with geometric standard deviations of about two. Because individual variations in uptake and retention will vary less from year to year than the variation between individuals, the dose-factor variability is held constant from year to year for a single realization of the dose estimate and only varied for additional realizations.

One additional uncertainty term is needed for the non-^{90}Sr radionuclides to address the ratio of intakes of these nuclides to ^{90}Sr. This is the term f_L^r, the annual ratio of nuclide-to-^{90}Sr in the intake for location *L* defined in Section 2. Because the intakes were primarily from drinking water, the intakes are proportional to the estimated concentrations of these radionuclides in river water. These ratios are currently estimated based on the results of the Techa River model (Vorobiova and Degteva 1999). Thus, uncertainties in the intake are directly proportional to uncertainties in predicted concentrations in river water. Based on the data presented in Vorobiova and Degteva (1999), the predicted concentrations could vary by up to 50% with different selection of transport parameters based on available data. For the uncertainty

analysis, a uniform distribution between 0.5 and 1.5 has been used for each radionuclide. This is an area for future evaluation. Sensitivity analyses for Muslyumovo indicate that this uncertainty contributes very little to the total uncertainty for red bone marrow doses, because the internal doses are dominated by the contribution from ^{90}Sr. The uncertainties in this term are relatively more important for organs of the gastrointestinal tract, because more of the dose resulted from these other radionuclides.

The conversion factors from absorbed dose in air to absorbed dose in organ o, A_o, are presented in Table 5 and have a weak dependence on radiation energy. However, there is a large plateau in the energy-dependent response between about 0.08 and 1.3 MeV (Eckerman and Ryman 1993), which are the energies of interest for this study. There is also a minor variation as a function of body mass, as captured and reflected in Table 5 for various ages. This parameter will be slightly variable for individuals of different weights; the distribution is assumed to vary by about 10 percent.

The terms T_1, T_2, and T_3, while ideally coming from individual data, are currently assigned generic values, depending on the age of the individual in year y. Based on the discussion of various lifestyle surveys presented in Vorobiova et al. (1999a) for individuals, these times are assumed to vary by up to 30%. They are allowed to change from year to year in order to account for individual circumstances. In implementation, the smaller values T_1 and T_2 are varied randomly, and T_3 is constrained so that the total fraction equals the fraction of the year spent in contaminated zones near the river (Table 4).

The external dose rates $D_{Riv,L,y}$, $D_{Out,L,y}$, and $D_{In,L,y}$ are derived from measurements, or alternatively, from the radionuclide contents of sediment calculated with the model of Vorobiova and Degteva (1999). The ranges of modeled or measured dose rates near the river bank are presented for each village in the Appendix to Vorobiova et al. (1999a). These ranges may be used to define the distribution of $D_{Riv,L,y}$.. The parameters $D_{Out,L,y}$, and $D_{In,L,y}$ are derived from $D_{Riv,L,y}$ using river-bank-to-residence-area dose-rate ratios and indoor-to-outdoor dose-rate ratios; such values and ranges are also presented in the Appendix to Vorobiova et al. (1999a). Because the actual distance of an individual's residence from the river is not yet known, it is equally likely that specific individuals could live in any house. Therefore, the bank-to-residence and indoor-to-outdoor dose-rate ratios are treated as uniform distributions between the lower and upper observed bounds.

In order to estimate the uncertainty of the dose estimates calculated using the TRDS-2000, a Monte Carlo version of the TRDS is currently under development. Examples of the application of the uncertainty analysis are provided in the following sections for external and internal exposures.

6.2. UNCERTAINTY IN EXTERNAL EXPOSURE

Estimation of uncertainty in external dose is illustrated with example Case History 1 from Section 3.3. This adult was exposed in Metlino from 1950 through February 1955. The key parameters necessary for the calculation are presented in Table 11. The ranges, and distribution shapes for these parameters are provided in Table 14. All of these parameters are described in Vorobiova et al. (1999a).

The distribution of dose to red bone marrow calculated using these distributions of input parameters is illustrated in Fig. 10. The parameters that describe this distribution are outlined in Table 15.

The distribution of external dose to RBM shown in Fig. 10 is the result of combining the distributions of all input parameters. As presented in Table 15, the 95% confidence range for this individual's dose is 0.27 to 0.84 Gy. The mean of 0.40 is slightly lower than the deterministic value of 0.42 presented in Table 11. The distribution in Fig. 10 appears to be lognormal, even though all of the input parameters are uniformly distributed. This is typical; this result occurs for most multiplicative models such as the one used here. A sensitivity analysis indicates which parameters contribute to the uncertainty. The key parameters for this dose distribution are listed, in terms of their contribution to the variance, in Table 16.

Table 14. Range and distribution type for parameters used in the calculation of external dose to the red bone marrow.

Parameter	Range	Distribution
D_{Riv} 1950	2.4–3.1	Uniform
D_{Riv} 1951	8.8–15	Uniform
D_{Riv} 1952	3.3–5.0	Uniform
D_{Riv} 1953	4.0–4.1	Uniform
D_{Riv} 1954	2.0–2.4	Uniform
D_{Riv} 1955	0.63–0.77	Uniform
T_1	0.012–0.022	Uniform
T_2	0.20–0.37	Uniform
A_0 for red bone marrow	0.63–0.83	Uniform
Bank-to-residence dose ratio	10–600	Uniform
Indoor-to-outdoor dose ratio	0.12–1.0	Uniform

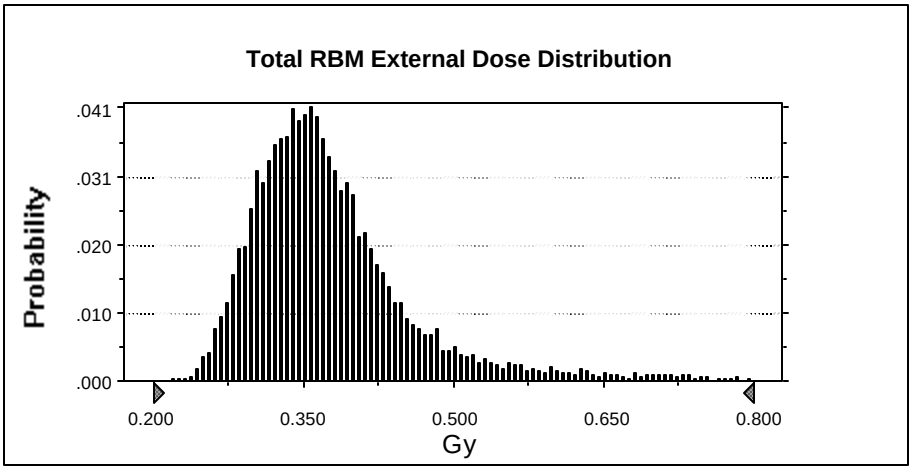
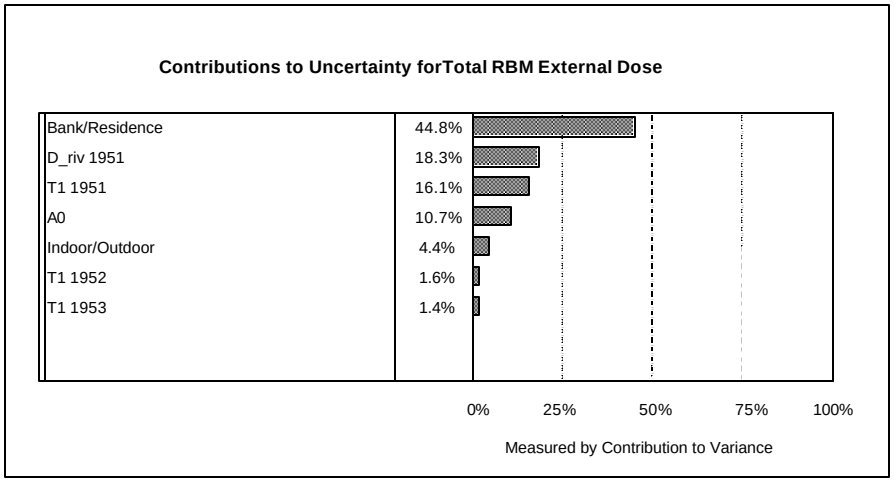


Fig. 10. Distribution of red bone marrow external dose for example Case History 1.

Table 15. Parameters of calculated external and internal dose distributions for Case Histories 1 and 2.

Percentile	External Dose Gy	Internal Dose Gy
2.5%	0.27	0.12
5.0%	0.28	0.23
50.0%	0.37	0.92
95.0%	0.65	2.8
97.5%	0.84	3.7
Mean	0.40	1.1
Median	0.37	0.92
Standard Deviation	0.15	0.94
Variance	0.022	0.88
Skewness	4.0	2.5
Kurtosis	26	13
Coeff. of Variability	0.37	0.83

Table 16. Key parameters contributing to uncertainty in external dose for Case 1.



The parameters in the external dose calculation for Case History 1 with the greater influence on the uncertainty are the ratio of dose rates on the riverbank with those in the residence area, and the time spent on the riverbank (in various years). Combined, these parameters account for nearly two-thirds of the uncertainty in external dose. The results for this Case History show that the 90% range is about a factor of four. This will vary for individuals from other villages, where the range of riverbank-to-residence dose rate ratio differs. However, it is a rough approximation of the external dose uncertainty for most of the TRC.

The uncertainty in the parameters related to time spent near the river are unlikely to be much improved through future research, because the events took place about 50 years ago, and

even an extensive interview program with the study subjects is not likely to provide substantial improvements. However, the most important parameter is related to the location of the individuals' houses within the village the ratio of dose rate at the river to that where the persons spent most of their time. This parameter could be improved with individual-specific data, specifically, correlating the subjects' home addresses with individual locations within the villages. This is a profitable area for future improvements.

6.3. UNCERTAINTY IN INTERNAL EXPOSURE

Estimation of uncertainty in internal dose is illustrated with example Case History 2 from Section 3.3. This adult was exposed in Ibragimovo from 1950 through June 1953, and then moved to Muslyumovo through 1959. The key parameters necessary for the calculation are presented in Table 12. Only three parameter distributions are necessary to estimate the uncertainty of the total dose for this individual. The Individual-to-Model Ratio accounts for the combined variability of the reference intake and individual metabolism. Values are needed for both Ibragimovo and Muslyumovo, as the individual lived in these two locations. The distribution is obtained from the data presented in the Appendix of Degteva et al. (1999). The only other parameter needed is the range of the ^{90}Sr-dose conversion factor exclusive of the uptake and retention variability. As discussed in Section 6.1 this is approximated as a lognormal distribution with a geometric standard deviation of 1.25.

The distribution of dose to red bone marrow calculated using these distributions of input parameters is illustrated in Fig. 11. The parameters that describe this distribution are outlined in Table 14. As presented in Table 14, the 95% confidence range for this individual's dose is 0.12 to 3.7 Gy. The mean of 1.1 is slightly higher than the deterministic value of 0.95 presented in Table 3, but the median is slightly less at 0.92. The distribution in Fig. 11 is somewhat skewed, and the discontinuities of the underlying *IMR* distribution for Ibragimovo are apparent.

A sensitivity analysis again indicates which parameters contribute to the uncertainty, and the results for this case are given in Table 17. Note that the dominant parameter is the distribution of Individual-to-Model Ratios for Ibragimovo, but that the *IMR* for Muslyumovo is not included. This is because about 99% of the dose results from exposures in Ibragimovo, and the added variability around the 1% of the dose from Muslyumovo is immaterial. The results for Case History 2 show that the 95% range is about a factor of 30. This will vary for individuals from other villages depending on the range of the *IMR*'s for that village. The 95% range for the *IMR*'s for Ibragimovo is about 20, for other villages the *IMR*'s can range from about 10 to 50, when no grouping is made for drinkers versus non-drinkers of river water.

The uncertainty in internal dose could be greatly reduced in future work by using the actual individual whole-body count results for individuals who have them, and by grouping individuals into households, drinkers versus non-drinkers of river water, or other groups related to individuals who have WBC records, for those individuals who do not.

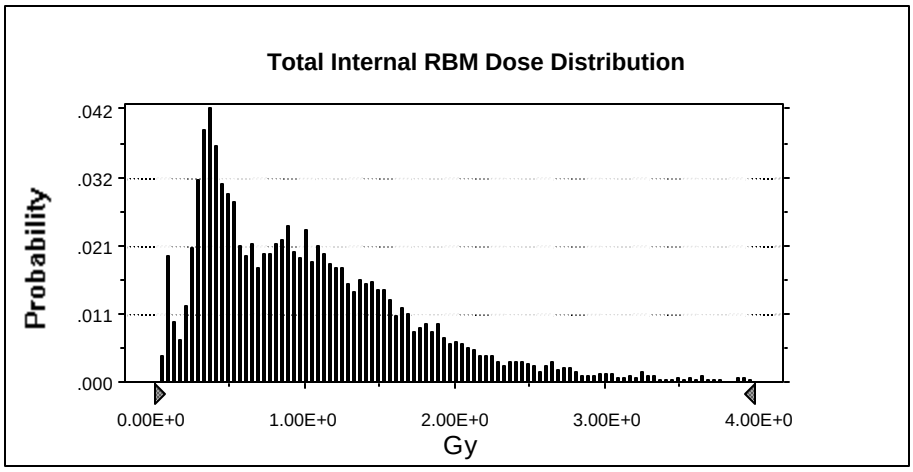
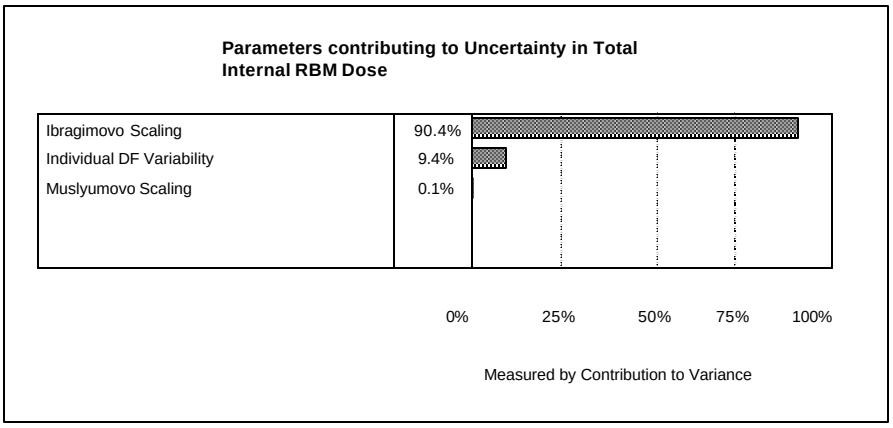


Fig. 11. Distribution of red bone marrow internal dose for example Case History 2.

Table 17. Key parameters contributing to uncertainty in internal dose for Case 2.



6.4. UNCERTIANTIES IN TRDS-2000 RESULTS

To demonstrate the magnitude of the uncertainties in the dose estimates, the approach to estimating uncertainties has been applied to reference individuals for each of the main Techa River settlements. The reference individuals are adult, full-time residents of the villages during the period of the larger releases, 1950–1956. The doses are all for the endpoint of 1980, 30 years after the initiation of the exposures.

Tables 18, 19, and 20 illustrate the results for external, internal, and total doses to red bone marrow for the villages of Metlino on the upper Techa River, and Muslyumovo and Brodokalmak on the middle Techa. Because the distributions are not symmetrical, percentiles are presented. It can be seen that external exposures contribute a large portion of the dose in Metlino, but only a small portion of the dose for the villages on the middle and lower portions of

Table 18. Parameters of calculated RBM external dose distributions for reference individuals in Metlino, Muslyumovo and Brodokalmak, Gy.

Settlement	Percentiles				
	5	10	50	90	95
Metlino	2.9×10^{-1}	3.0×10^{-1}	3.6×10^{-1}	4.7×10^{-1}	5.6×10^{-1}
Muslyumovo	6.8×10^{-3}	7.2×10^{-3}	9.0×10^{-3}	1.6×10^{-2}	2.1×10^{-2}
Brodokalmak	3.9×10^{-3}	4.2×10^{-3}	6.1×10^{-3}	1.3×10^{-2}	1.56×10^{-2}

Table 19. Parameters of calculated RBM internal dose distributions for reference individuals in Metlino, Muslyumovo and Brodokalmak, Gy.

Settlement	Percentiles				
	5	10	50	90	95
Metlino	2.6×10^{-2}	7.0×10^{-2}	4.0×10^{-1}	1.09	1.5
Muslyumovo	7.5×10^{-2}	1.5×10^{-1}	6.5×10^{-1}	1.52	1.9
Brodokalmak	5.8×10^{-3}	6.5×10^{-3}	1.0×10^{-1}	5.6×10^{-1}	7.7×10^{-1}

Table 20. Parameters of calculated total RBM dose distributions for reference individuals in Metlino, Muslyumovo and Brodokalmak, Gy.

Settlement	Percentiles				
	5	10	50	90	95
Metlino	3.9×10^{-1}	4.4×10^{-1}	7.8×10^{-1}	1.50	1.89
Muslyumovo	8.7×10^{-2}	1.6×10^{-1}	6.6×10^{-1}	1.53	1.88
Brodokalmak	1.1×10^{-2}	1.3×10^{-2}	1.1×10^{-1}	5.7×10^{-1}	7.8×10^{-1}

the river. The 90th percentile range of uncertainty on the external dose is only about a factor of two for the upper river and increases to about a factor of four for the lower river. The 90th percentile range of internal dose is much larger, from about 60 for Metlino to over two orders of magnitude for the villages further downstream. This is reflected in the total dose estimates: The 90th percentile range in total dose for Metlino is less than a factor of five, but for Brodokalmak it is nearly a factor of 70.

The approach to uncertainties is applicable to all organs. Tables 21, 22, and 23 illustrate the results for external, internal, and total doses to the lower large intestine (LLI) for the same three villages. These doses are typical of walled organs. Similar results are presented in Tables 24, 25, and 26 for testes, representing other soft tissues.

Table 21. Parameters of calculated LLI external dose distributions for reference individuals in Metlino, Muslyumovo and Brodokalmak, Gy.

Settlement	Percentiles				
	5	10	50	90	95
Metlino	0.25	0.27	0.32	0.41	0.48
Muslyumovo	0.006	0.006	0.008	0.014	0.018
Brodokalmak	0.003	0.004	0.005	0.011	0.014

Table 22. Parameters of calculated LLI internal dose distributions for reference individuals in Metlino, Muslyumovo and Brodokalmak, Gy.

Settlement	Percentiles				
	5	10	50	90	95
Metlino	0.007	0.030	0.20	0.71	1.0
Muslyumovo	0.030	0.059	0.26	0.73	1.0
Brodokalmak	0.002	0.002	0.034	0.23	0.35

Table 23. Parameters of calculated LLI total dose distributions for reference individuals in Metlino, Muslyumovo and Brodokalmak, Gy.

Settlement	Percentiles				
	5	10	50	90	95
Metlino	0.31	0.35	0.54	1.1	1.4
Muslyumovo	0.039	0.068	0.27	0.74	1.0
Brodokalmak	0.007	0.008	0.041	0.24	0.36

Table 24. Parameters of calculated testes external dose distributions for reference individuals in Metlino, Muslyumovo and Brodokalmak, Gy.

Settlement	Percentiles				
	5	10	50	90	95
Metlino	0.32	0.33	0.40	0.52	0.62
Muslyumovo	0.007	0.008	0.010	0.018	0.024
Brodokalmak	0.004	0.005	0.007	0.014	0.018

Table 25. Parameters of calculated testes internal dose distributions for reference individuals in Metlino, Muslyumovo and Brodokalmak, Gy.

Settlement	Percentiles				
	5	10	50	90	95
Metlino	0.001	0.004	0.029	0.122	0.18
Muslyumovo	0.001	0.002	0.012	0.043	0.062
Brodokalmak	4.0×10^{-5}	6.3×10^{-5}	0.001	0.008	0.012

Table 26. Parameters of calculated testes total dose distributions for reference individuals in Metlino, Muslyumovo and Brodokalmak, Gy.

Settlement	Percentiles				
	5	10	50	90	95
Metlino	0.34	0.37	0.45	0.62	0.74
Muslyumovo	0.011	0.012	0.024	0.056	0.075
Brodokalmak	0.005	0.005	0.009	0.019	0.023

7. DISCUSSION

Information presented in this document is intended to review and summarize the work that has been accomplished to date by work on Project 1.1 of the JCCRER. Although work on dose reconstruction for the Techa River Cohort had been ongoing for many years in Russia, the cooperative work and greater resources made available through this joint project have enabled substantial improvements to be made in the Techa River Dosimetry System over the last five years.

As would be expected in the course of making the improvements in the dosimetry system, substantial changes (in some cases as much as an order of magnitude) have occurred in the estimates of dose for the members of the ETRC. There are many underlying reasons why the original estimates were biased or uncertain and why it has been possible to make improvements. In some cases the initial estimates of dose were performed for radiation-protection purposes in order to effect decisions on relocation or lifestyle restrictions; this conservative bias was particularly apparent for external dose. Removal of this bias was only possible following a detailed review of existing information and the substitution of more realistic estimates for the previous conservative ones.

For some parameters no directly useful measurement data existed, and it had been possible previously to make only rough approximations. Example situations included the concentration of short-lived radionuclides in river water and the concentration of gamma-

emitting radionuclides in sediments and in soil near the shoreline. A marked step forward was achieved by the completion of the Techa River Model (Vorobiova and Degteva 1999), which embodied years of experience in source-term reconstruction by the members of the Mayak Central Laboratory and the Moscow Institute of Biophysics and the systematic analysis of all available data on river hydrologic parameters and on measurements of radionuclides in river water and sediments (Vorobiova et al. 1997).

Some of the key features of the revised doses are that the internal doses to some tissues, particularly of the gastrointestinal tract, have increased by up to a factor of two due to the inclusion of short-lived radionuclides. Of more concern, however, are the reductions by up to a factor of ten of the external doses for many members of the ETRC. This latter change has evoked strong expressions of concern from the Russian team of epidemiologists working on companion studies, as the change in dosimetric values will produce a major shift in the estimates of radiogenic risk that are being developed from the study of the ETRC. Because the exposure of the members of the ETRC is unique and the study of their experience is potentially very valuable, the members of the Project 1.1 dosimetry team again emphasize the importance of pursuing studies that can provide experimental validation of the revised doses.

Preliminary and limited validation of the revised doses has been achieved, but much more work is needed. Of particular promise is the near term examination of dose to teeth, as measured by electron paramagnetic resonance spectrometry.

7.1. EVALUATION OF THE EXPERIENCE GAINED BY TRDS-2000 DEVELOPMENT

During the course of the past years a plan of work has been followed that was outlined in the proposal document. While some deviations have occurred as experience accumulated, the work has followed the plans rather faithfully. As indicated in more detail below, the analysis of uncertainty has proceeded more rapidly than anticipated; work involved with the upgrade of the SICH-9.1 WBC has gone more slowly than planned.

The results of some of the more significant developments are evaluated below.

7.1.1. Review of historical data

One of the early activities undertaken was to review all known sources of historical data relating to

- Discharges into the Techa River from the Mayak Production Association;
- Hydrologic characteristics of the Techa River System and changes (impoundments or other changes, such as canals, etc.) over the years;
- Measurements of concentrations of radionuclides in river water;
- Measurements of concentrations of radionuclides in sediments and soils;
- Measurements of external gamma-exposure rates at the shoreline and in the residence areas; and
- Observations on amounts of time residents spent near the shoreline and in other locations.

As a result of this review the investigators are now satisfied that they have access to all data known to be relevant. A feasibility study was also conducted under the auspices of the JCCRER by personnel at the MPA and U.S. colleagues. The results (Mokrov et al. 1999) of this feasibility study did not reveal any new information that was not previously available. While there is always a chance that some obscure, but useful documents might be found or that some additional useful data might become available from newly declassified documents, this possibility now seems remote.

Our review of available data was published as the Milestone 1 document (Vorobiova et al. 1997), and a summary was published in the open, peer-reviewed literature (Vorobiova et al. 1999b). This documentation in the open literature of the analytical review of historical data is viewed as a major step in establishing the credibility of the dosimetry for the ETRC. It was also a necessary step leading to follow-on developments.

7.1.2. Development of the Techa River Model

Unfortunately, the available measured data in themselves are not sufficient to support a complete dose-reconstruction effort. This is because the measured concentrations in river water did not include all radionuclides, some early measurements of concentrations in water and in sediments were only of gross-beta activity, and the measurements did not start until some of the major releases had already occurred. Thus, in order to provide a dose-estimation system (the TRDS) that covers all time periods and locations, it was necessary to codify the existing results and other fundamental quantities (such as the radionuclide-dependent partitioning between water and sediments) into the "Techa River Model." This model was developed and published by Vorobiova and Degteva (1999). Because of a desire not to overinterpret the existing results, the model developed is the simplest possible that is consistent with the observations.

The development of this model has had a significant impact, and its use has been critical for the follow-on improvements that have now been incorporated in the TRDS-2000. Prior to the development of this model several assumptions had been made that were known, or at least suspected, to be gross oversimplifications of the real situation. For example, it had been assumed previously that the relative concentrations in river water as a function of downstream distance were the same for all radionuclides, that is, all relative concentrations were the same as for ^{90}Sr. As a corollary it had also been assumed that the relative concentrations in downstream sediments had also been the same for all radionuclides. Implementation of the more appropriate relationships has led to major (and quantitatively significant) changes in the calculated values of both internal and external doses. External doses are now more important for the upper Techa locations (due to the rapid absorption of ^{137}Cs and other gamma-emitting radionuclides onto sediments) and much less important for middle to lower Techa locations. Short-lived radionuclides, which were not measured originally, are now incorporated into the model and are estimated to have made substantial contributions to dose to gastrointestinal organs for residents on the upper Techa River.

7.1.3. Recalibration and upgrade of the SICH-9.1 whole body counter (WBC)

One of the features of the exposure of the general population to the MPA releases is that the most important radionuclide in terms of internal dose is ^{90}Sr. This radionuclide, once ingested, is incorporated into bone tissue from which it is eliminated only very slowly. Thus, it

has been possible to secure bone tissue at autopsy and to measure the ^{90}Sr content in such tissue. And, more usefully, it is possible to measure the ^{90}Sr content in living persons with the use of a whole body counter that is specially designed to permit the detection of bremsstrahlung associated with the emission of the high-energy beta particle by ^{90}Y, the short-lived progeny of ^{90}Sr. Over half of the members of the ETRC have been counted one or more times with this WBC. This data set is extremely important for the calculation of dose for the members of the ETRC, as these measurements are related closely to dose quantities. The examination of distributions of ^{90}Sr-body burdens on a village-by-village basis has also been valuable in defining the uncertainty in internal dose for the dose-reconstruction system.

Because of the importance of these measurements, a key issue has been to ensure the validity of these measurements and to update the system with modern detectors and electronics. The initial calibration of the detector system had been accomplished with perishable cadaver-related surrogate systems, but was only done once during a detailed study. Routine calibration of the system with point and extended sources had always been done, but no further measurements had been made with phantom systems.

In order to verify the initial calibration of the old system a modern phantom was constructed (Kovtun et al. 2000) with ^{90}Sr incorporated into its bone-simulant "tissue." Measurements of this phantom (and other phantoms of less critical configuration to simulate a human with body burdens of ^{40}K and ^{137}Cs) with the old WBC system have verified the correctness and persistence of the original calibrations (Kozheurov et al. 1998). Thus, a very important keystone of the TRDS-2000 (and predecessor models) has been validated.

The existing WBC has also been upgraded with the purchase of new detectors and electronic systems. These upgrade components were installed in July 1999. It is unfortunate that the new system has not functioned, except for the period of its acceptance trial. Although the system is under warranty the provider has not yet been able to rectify this situation, which appears to be due primarily to the nonfunctioning of the four phoswich detectors. The warranty on the system has been extended by the provider and efforts continue to resolve the issues.

7.1.4. Review of internal doses

A review of the methods for the calculation of internal dose in the TRDS was published as the Milestone 3 report (Tolstykh et al. 1998). The calculation of the main component of dose, which is from ^{90}Sr, was always grounded firmly. This was due to the extensive amounts of data from autopsy materials and from the whole body and teeth counts of half of the members of the ETRC. However, it has been possible to make major improvements in the methods of dose reconstruction with the implementation of the Techa River Model. Now the doses to organs of the gastrointestinal tract are modeled more accurately, due to the inclusion of short-lived radionuclides in the TRDS.

7.1.5. Review of external doses

Re-examination of the external dose estimated for the members of the ETRC has resulted in major changes. The reasons for these changes have been detailed in the Milestone 6 report (Vorobiova et al. 1999a); an open literature publication is also in press (Degteva et al. 2000c).

The improvements in estimates of external dose were made possible by three main factors. First, the development of the Techa River Model led to an enhanced ability to model the decrease in exposure rate downstream of the point of release and the build-up (and then decline over the longer term) in exposure rate with time since the releases began. Prior to the development of the model assumptions had been made that the decrease of exposure rate with downstream distance in 1951 was the same as the decrease in concentration of beta-emitting radionuclides in river water and that the exposure rates in 1950 and 1951 were the same. Both of these assumptions proved to be conservative. Second, the dose rates within residence areas had been assumed to be the same for the entire settlement and were based upon the first line of households near the river. The collection of all exposure-rate-measurement data and their assessment (Vorobiova et al. 1999a) have led to a village-by-village evaluation of these data and the calculation of a household-weighted average value of residence area-to-river bank exposure rates. Third, the behavior factors (amount of time spent near the river) used previously had been derived for radiation-protection purposes (e.g., implementation of decisions regarding relocation and restrictions) for critical groups and have proven to be overestimates.

Thus, the revisions in estimates of external dose have been a major improvement in the TRDS. Such major changes, however, are inevitably controversial and point out the need for validation studies.

7.1.6. Evaluation of uncertainty

Another significant first has been the evaluation of the uncertainty in the dose estimates; this topic is discussed in detail in Section 6 of this report. Two milestone reports (Degteva et al. 1999; Napier et al. 2000) have also been published on this subject. The initial plans for this task were limited and work has progressed more rapidly than planned. Such work is viewed as very important for two primary reasons:

- An accurate knowledge of the uncertainty in the doses should be important in evaluating the results of any derivation of risk factors from the study of the ETRC, and
- Knowledge of the sources of uncertainty in the doses should have a powerful impact in directing future activities, i.e., focusing future work on reducing the major sources of uncertainty that are amenable to reduction.

As discussed above in Section 6 several major sources of uncertainty in both internal and external doses have been identified; these clearly fall into two categories. Some uncertainties do not seem amenable to reduction, but others clearly do. An example of the latter is the uncertainty in the external dose due to unknown home location. The association of each individual with a specific position of his house within be very valuable. Such data are available in old tax books and other records and could be used for this purpose. The task would not be easy for these long abandoned locations and for this large number of persons. The possibility of a major reduction in uncertainty, however, is compelling.

7.2. POSSIBILITIES OF ADDITIONAL IMPROVEMENTS IN DOSIMETRY (TRDS-2005)

The substantial improvements in the Techa River Dosimetry System have led to significant changes in the estimates of dose for the members of the ETRC. Further major

improvements in the dosimetry system to support companion epidemiologic studies can be made by

- Further study of uncertainty with the goal of reducing uncertainty in the final dose estimates;
- Study of other sources of dose that could confound the analysis of the epidemiologic data for the members of the ETRC; and
- Validation of the dose estimates, particularly of the revised estimates of external dose.

Much attention in this report has already been focused on the value of the preliminary results of the analysis of uncertainty, and how these results could be used to direct work on the major sources of uncertainty that can be reduced. The analysis of uncertainty has not yet been formalized into TRDS-2000 through the creation of a Monte Carlo version of the TRDS code. This is a major task that should be given early priority. It is evident that there are two relatively large sources of uncertainty that can be reduced. One is the association of a particular individual with the location of the house within which he lived. This is an important variable affecting external dose. At the present time a household weighted distance of homes from the river is being assumed with attendant large uncertainty in the estimated dose. Another major source of uncertainty relates to the source of drinking water. Based upon the data in the Milestone 8 report (Degteva et al. 1999) on direct measurements of body burdens, it seems clear that this source of uncertainty might be reduced in a variety of ways. The preferred way would be to use the measured body burdens directly as individual-input data. This is not being done at the present time, as about half the members of the cohort do not have such measurements. However, it is possible to associate family members into households wherein one or more other persons did have such measurements: The assumption could then be made that all members of the household had the same source of drinking water. Another helpful aspect will the continuation of counting of additional members of the cohort within the SICH-9.1 whole body counter.

In terms of confounding sources of dose to the members of the ETRC, there are two known sources. One is the East Urals Radioactive Trace (EURT), or the Kyshtym explosion in 1957. This source of radioactive material is known to have impacted a few thousand members of the ETRC who had been relocated away from the Techa River and into the path of the future EURT. The ability to calculate doses from the EURT for this subset of the ETRC already exists in the TRDS-2000 code. However, there has not been an evaluation of the existing data to support the necessary input parameters on time- and location-dependent intake rates of radionuclides and on external gamma-exposure rates.

Another potentially major source of confounding exposure is the gaseous releases through the radiochemical plant stacks at the MPA. Large releases of ^{131}I and other radionuclides are known to have occurred.

Finally, the validation of the new estimates of external doses is considered to be a critical factor in the continuing credibility of the TRDS-2000 results and the companion epidemiologic studies they support. Recent successes in the measurement of doses by thermoluminescence of natural materials and by electron paramagnetic resonance (EPR) of tooth enamel have

demonstrated that these measurements can be applied to the Techa River situation. However, the measurements can be difficult and must be supported by extensive modeling to support the interpretation. For example, the time-dependent, complicated source geometries must be modeled in order to interpret the results of thermoluminescence measurements. The EPR measurements also have complications in the fact that the measurements of "external" dose are complicated by the presence of ^{90}Sr in tooth enamel. Thus, an EPR measurement by itself is not sufficient as a validating measurement without some accompanying knowledge of the contribution of ^{90}Sr and perhaps other radionuclides.

8. CONCLUSIONS

Substantial improvements have been made in the Techa River Dosimetry System (TRDS-2000). These improvements have brought substantial changes in the estimates of dose for the members of the ETRC.

Limited data on validation generally support the new estimates, but validation work is considered as an important task for the future.

The first preliminary results of the analysis of uncertainty in the TRDS doses has provided valuable insight into how work can be directed to reduce uncertainty in the dose estimates. The further study of uncertainty, effective implementation of a Monte Carlo version of the TRDS-2000 code, and work on reducing uncertainty are important aspects of future plans.

There are known to be confounding sources of dose for some members of the ETRC, such as the EURT and the gaseous emissions from the MPA. Better means of estimating these confounding sources of dose should be part of a future program of investigation of this cohort.

The primary goal of this project on improvements in the Techa River Dosimetry System has been met. The dosimetry team is ready for the planned year 2000 "freeze" of the cohort.

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